WHITE PAPER NO. 16 – wLFRM DEVELOPMENT AND CALIBRATION FOR THE LOWER FOX RIVER/GREEN BAY REMEDIAL INVESTIGATION, FEASIBILITY STUDY, PROPOSED REMEDIAL ACTION PLAN, AND RECORD OF DECISION

Response to a Comments on the

WHOLE LOWER FOX RIVER MODEL

This Document has been Prepared by

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ABSTRACT

During the comment period, the Wisconsin Department of Natural Resources (WDNR) and United States Environmental Protection Agency (USEPA) received comments regarding the site-specific water quality model for the Lower Fox River. Commenters took issue with the development and application of the Whole Lower Fox River Model (wLFRM) (WDNR, 2001) conducted for the *Remedial Investigation for the Lower Fox River and Green Bay, Wisconsin* (RI) (RETEC, 2002a). This White Paper presents a response to these comments, in a response/comment format, including overviews of field observations, model development, and model performance assessments.

The wLFRM is the product of more than 10 years of field study and four generations of model development and performance assessment efforts, and included the direct, collaborative involvement of the Fox River Group (FRG) and consultants through the Model Evaluation Workgroup (Workgroup). Development of the wLFRM is consistent with the information developed by the Workgroup in a series of Technical Memoranda (TM). The TM define values for critical model features such as flows, loads, initial conditions, boundary conditions, and sediment transport represent the most detailed description possible of pertinent river conditions using existing data and provided the majority of the information necessary for model development. The development histories of the model framework, IPX 2.7.4, and its application to the Lower Fox River have been extensively documented through numerous reports and peer-reviewed journal publications.

Key findings, supported by wLFRM results, are that PCBs exported to Green Bay must originate from the River sediments, and the rate at which PCB levels decline is relatively slow. Model parameterizations are consistent with observations and published literature. Model results are also consistent with observations and the results of supporting studies such as the PCB trend analysis contained in the Time Trends Report (TMWL, 2002). Given the results of the performance assessment, the wLFRM was judged to be an appropriate tool to evaluate the relative differences between remedial alternatives presented in the RI and the *Feasibility Study for the Lower Fox River and Green Bay, Wisconsin* (FS) (RETEC, 2002b).

1 INTRODUCTION

The selection of a remedy to address polychlorinated biphenyl (PCB) contamination of the Lower Fox River (LFR) and Green Bay (GB) was the end result of an extensive evaluation process consistent with USEPA guidelines for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) projects. The remedy is described in the Proposed Remedial Action Plan (the Proposed Plan) that was issued in October 2001 and the Record of Decision (ROD) for Operable Units 1 and 2 being issued in December 2002 by the USEPA and the WDNR. The Proposed Plan and ROD were developed from information presented in the LFR/GB RI/FS (RETEC, 2002a, 2002b). The RI/FS included information from numerous supporting studies to the help select the remedy. A description of how these supporting studies contributed to the remedy selection process is described in *White Paper No. 9 – Remedial Decision-Making in the Lower Fox River/Green Bay Remedial Investigation, Feasibility Study, Proposed Remedial Action Plan, and Record of Decision* (WDNR, 2002a).

Among the supporting studies considered during the remedy selection process were site-specific chemical transport and biota models for the Lower Fox River and Green Bay. One of those site-specific models is the "whole" Lower Fox River model (wLFRM). The wLFRM is the result of numerous assessments of Lower Fox River water quality model performance and represents the fourth generation of model development. The wLFRM was developed to examine the movement and distribution (transport and fate) of PCBs in the Lower Fox River based on consideration of the observed physicochemical properties of the chemical, PCB concentration trends in water and sediment, and observed interactions between the water column and sediment bed such as resuspension and net burial (WDNR, 2001a).

This White Paper addresses issues concerning wLFRM development and calibration for the LFR/GB RI/FS, the Proposed Plan, and ROD. Development of the wLFRM was guided by comparisons to field observations. The usefulness of the wLFRM was determined by comparing model results to observations conditions. In order to understand the development and calibration of wLFRM, it is therefore necessary to first understand observed conditions for the River. A summary of observed conditions for the River is presented in Section 2 of this White Paper. Model development and calibration are then guided by this understanding of the observed conditions. A summary of model development and calibration is presented in Section 3. Comparisons between model results and observed conditions are then summarized in Section 4. Discussions of wLFRM performance in light of comments received during the RI/FS public comment period are presented in Section 5. Finally, conclusions regarding wLFRM performance and usefulness in the RI/FS are presented in Section 6.

2 OBSERVED CONDITIONS IN THE LOWER FOX RIVER

PCBs are the main contaminant of human health and ecological concern in the Lower Fox River and Green Bay. PCBs are a series of chlorinated organic chemicals that are hydrophobic, readily associate with sediments and fat tissues (lipids), and are believed to cause cancer, birth defects, and impair immune systems. PCBs were discharged to the River during the manufacture and recycling of carbonless copy paper. Approximately 317,000 kg of PCBs were discharged to the River between 1954 and 1997 (WDNR, 1999a). Present PCB levels exceed water quality standards and contaminate fish to unsafe levels. As a result of this extensive contamination, fish consumption advisories for the River have been in place since 1976.

The wLFRM was developed to examine the transport and fate of PCBs in the Lower Fox River and was calibrated using data collected as part of the USEPA 1989-1990 Green Bay Mass Balance Study (GBMBS), the 1994-1995 Lake Michigan Mass Balance Study (LMMBS), and other field studies over the period 1989 to 1995 (WDNR, 2001a). The 1989 to 1995 timeframe is the period over which the River was sampled in the most extensive and comprehensive manner. Additional studies completed since 1995 were also considered. Field data define observed conditions and trends. Model performance is assessed by comparing how closely model results compare to observed conditions and trends. For the Lower Fox River, field data allow the following conditions and trends to be defined:

1. Observed PCB trends in water;
2. Observed PCB trends in surface sediment;
3. Observed sediment bed elevations changes;
4. Rates of net sediment accumulation; and
5. Depths and rates of sediment mixing.

An overview of Lower Fox River conditions defined by field observations follows. More full descriptions of observed conditions for the River are presented in the reports *Development and Application of a PCB Transport Model for the Lower Fox River* (WDNR, 2001a) and Technical Memorandum 3a (WDNR, 2001b).

2.1 OBSERVED SPATIAL AND TEMPORAL PCB TRENDS IN WATER

Observed spatial trends in Lower Fox River water column PCB concentrations were determined by examining PCB levels measured at different location from Lake Winnebago to the River mouth. The data show that PCB concentrations go from essentially non-detectable levels at Lake Winnebago, to levels in Little Lake Butte des Morts that exceed water quality standards, and progressively increase with location downstream. The most complete set of observations is for the period 1989 to 1995 and includes samples collected at up to six locations along the River: (1) Lake Winnebago (the dams at Neenah and Menasha at the head of the River), (2) Appleton, (3) Kaukauna, (4) Little Rapids, (5) De Pere, and (6) the River mouth at Green Bay. During the 1989-1990 GBMBS, samples were collected at all six locations at a number of times. Data for the Lake Winnebago, Appleton, De Pere and River mouth sites are presented in Figure 2-1. Given that all external PCB inputs (i.e. wastewater discharges) to the River are controlled, the data also demonstrate that residual PCB releases from River sediments are the present-day source of PCBs to the water column.

Observed temporal trends in Lower Fox River water column PCB concentrations were determined by examining PCB levels measured over time. Both seasonal and year-to-year trends were examined. The data show that consistent seasonal trends exist and that no significant year-to-year trend exists. Over time across all locations, there is a consistent trend of low PCB levels during winter months and higher levels during summer months. Over time, the most complete set of observations were collected at the River mouth. Regression analyses over the period 1989 to 1995 suggest that differences in water column PCB levels over time are not statistically significant.[1, 2] Data from the River mouth site over time are presented in Figure 2-2.

In summary, three conclusions may be drawn from these data: (1) ongoing PCB transport from sediments causes water column PCB levels to increase from essentially zero at the upstream limit of the River to levels that greatly exceed water quality standards throughout the River; (2) seasonal patterns of low PCB levels during winter months and higher levels during summer months exist; and (3) water column PCB concentration changes over time are expected to be slow or near zero.

2.2 Observed Spatial and Temporal PCB Trends in Surface Sediment

Observed spatial and temporal trends in Lower Fox River surface sediment PCB concentrations were determined by examining PCB levels measured at all locations between Lake Winnebago to the River mouth by position (distance from Lake Winnebago) and year of sample collection. Sediment PCB concentrations have been measured at approximately 850 horizontal locations and at many different depth intervals throughout the Lower Fox River. The most complete set of observations is for the period 1989 to 1995 with additional samples collected at further locations in more recent years. An overview of these data is presented in Technical Memorandum 2e (TM2e) (WDNR, 1999b). Accurate quantification of spatial and temporal PCB concentration trends in Lower Fox River sediments is complex. None of the data collection efforts were

1 Determinations of water column PCB trends are very difficult. PCB concentrations are affected by a wide range of physical factors including, river flow, suspended solids concentrations, temperature, seiching between the River and Bay, and also by differences in sample collection and analytical protocols over time. Even neglecting these confounding factors, any trend that may be inferred from these data is weak, explaining almost none of the data variability (very low r^2), not statistically significant ($p > 0.05$), and has a wide 95 percent confidence interval that ranges from a slight decreasing trend to a slight increasing trend over time.

2 Additional water column PCB samples were collected at the River mouth in 1997. Unfortunately, these data are not directly useful for estimating year-to-year trends because those sampling efforts used very different sample collection and analytical protocols. Without a means to account for the potentially large biases that can occur as a result of the different protocols, the 1997 data cannot be directly used for a trend assessment.

specifically designed to estimate PCB concentration trends over time. In addition to being collected at different horizontal and vertical intervals and at different times, cores from each sampling effort were generally analyzed using different analytical techniques and quantitation standards. The differences introduced as a result of spatial heterogeneity, temporal variability, and analytical bias confounds identification of possible trends. Consequently, the nature and influence of these confounding factors must be considered when estimating the scale of possible PCB trends.

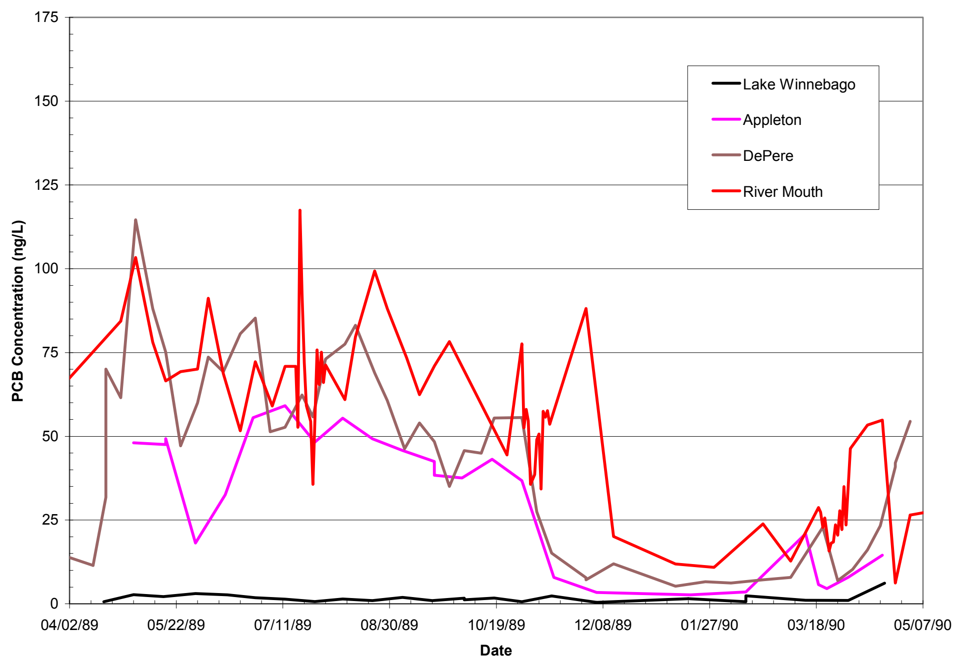

FIGURE 2-1 WATER COLUMN PCB CONCENTRATION FROM LAKE WINNEBAGO TO THE RIVER MOUTH

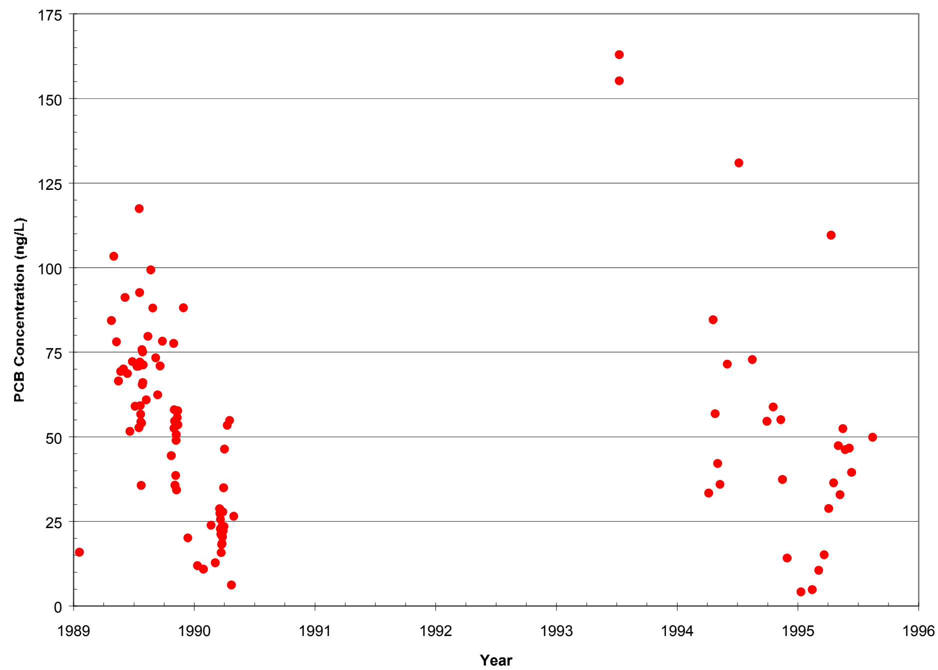

FIGURE 2-2 WATER COLUMN PCB CONCENTRATIONS AT THE RIVER MOUTH: 1989-1995

Considering the surface sediments (0-10 cm) of the entire River, as well as individual River reaches, the potential ranges of spatial and temporal PCB concentrations trends were examined. These results are presented in Figures 2-3 and 2-4 and Table 2-1. The results suggest that PCB concentrations generally decrease with distance downstream of Lake Winnebago. When expressed as an apparent annual rate of change, across the entire River PCB concentrations in the upper 10 cm of sediment appear to be increasing over time at an average rate of approximately 5 percent per year. However, the results also suggest that some apparent concentration increases over time may reflect the spatial heterogeneity of sediment PCB concentrations. As just one example of spatial heterogeneity, consider that surface sediment PCB concentrations in samples collected during 2001 from Little Lake Butte des Morts were higher than reported in any prior study. These data could be taken to suggest that PCB levels increased over time. However, given that there are no external PCB sources to the River, it is more likely that concentration differences over time represent spatial heterogeneity. Further, the trend analysis results also suggest that the year of sample collection describes very little of the variability of sediment PCB concentrations. Overall, the trend analyses indicate that PCB concentrations in any reach may increase, decrease, or stay the same over time. Further description of the trend analyses is presented in Appendix B of WDNR (2001a). Additional analyses based on different assumptions are presented by TMWL (2002).

In summary, four conclusions may be drawn from these data: (1) a spatial trend of generally decreasing sediment PCB concentration with distance from Lake Winnebago exists; (2) apparent PCB concentration changes over time may reflect the spatial heterogeneity of PCBs in the sediments; (3) at any individual location, sediment PCB concentrations may increase, decrease, or stay the same over time; and (4) the overall rate at which surface sediment PCB concentrations change over time is slow.

TABLE 2-1 INFERRED SURFACE SEDIMENT (0-10 CM) PCB CONCENTRATION TRENDS OVER TIME

Reach[3]	Inferred Rate of Change (%/year)	Rate at Lower 95% CL[4] (%/year)	Rate at Upper 95% CL (%/year)	Notes
1	-22.8 (-16.0 to -29.7)	-29.2 (-20.4 to -37.9)	-15.9 (-11.1 to -20.7)	Apparent trends may be attributable to shifts in sampling sites over time.
2	+41.8 (+29.3 to +54.4)	+22.2 (+15.4 to +28.9)	+64.4 (+45.2 to +84.0)	
3	-8.1 (-5.7 to -10.6)	-19.6 (-13.7 to -25.4)	+4.9 (+3.4 to+6.4)	Apparent trends may not be significantly different from zero.
4	0	-6.6 (-4.6 to -8.5)	+7.0 (+4.9 to +9.1)	
All	+5.6 (+3.9 to +7.3)	+0.8 (+0.6 to +1.1)	+10.6 (+7.4 to +13.8)	Significance of apparent trend unclear. Sampling efforts varied spatially and over time.

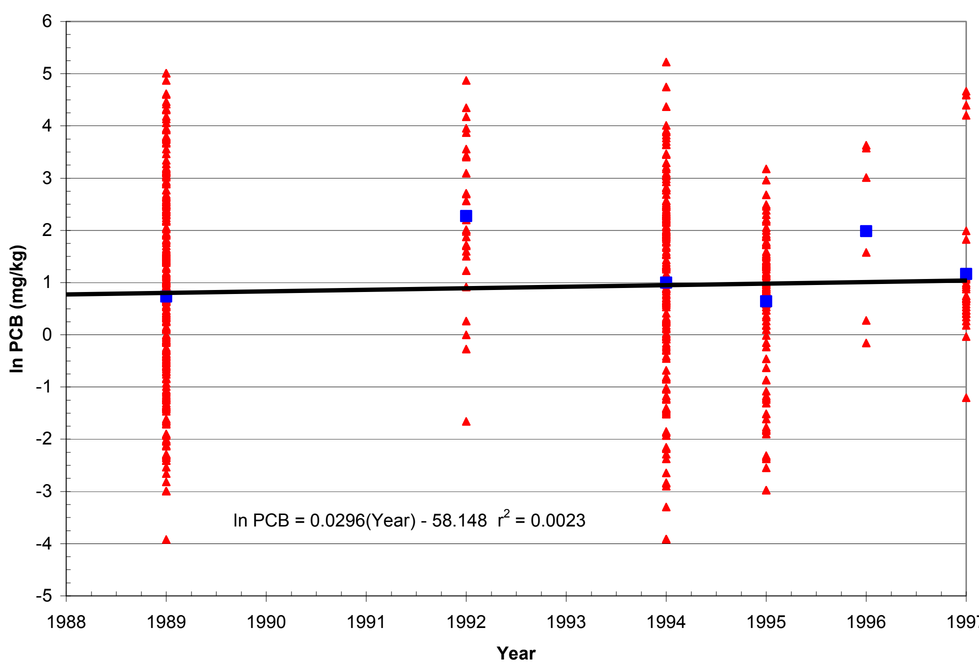

FIGURE 2-3 SURFACE SEDIMENT PCB CONCENTRATION TREND OVER TIME: ALL REACHES (0-10 CM)

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3 River reaches are defined in Table 3-2 of this report.

4 Confidence limit.

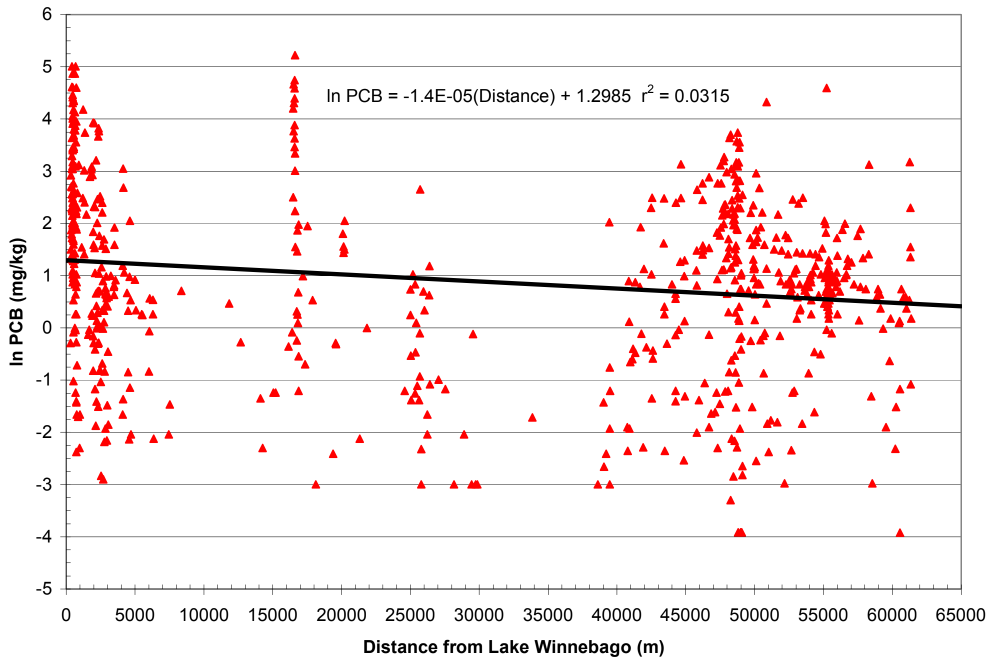

FIGURE 2-4 SURFACE SEDIMENT PCB CONCENTRATION TREND OVER SPACE: ALL REACHES (0-10 CM)

2.3 OBSERVED SEDIMENT BED ELEVATION CHANGES

Observed sediment bed elevation changes in Lower Fox River were determined by examining hydrographic survey results. These results indicate that the sediment bed of the Lower Fox River is not necessarily a stable environment for PCBs. At many locations large gross sediment bed elevations increases and decrease were observed over time, while over broad areas much smaller net changes in bed elevation were observed. As a result of bed elevation changes, the profile of PCBs in the sediment column may be altered. Where bed elevations decrease, the changing position of sediment-water interface may expose PCBs once located deeper in the sediments.

Sediment bed elevation dynamics were examined as part of Technical Memorandum 2g (TM2g) (WDNR, 1999c). In that effort, hydrographic surveys of the River conducted by the USACE, USEPA, and USGS were reviewed to describe sediment bed elevations at selected locations along the River for the period 1977 to 1998. Most of these data were collected downstream of the De Pere dam in the last 15 kilometers (seven miles) of the River. Sediment bed elevation changes are observed in both cross-channel and downstream profiles. Short-term (annual and sub-annual) average net sediment bed elevation changes at individual locations range from a decrease of 28 cm to an increase of 36 cm. Long-term (several years) average net elevation changes at individual locations range from a decrease of more than 100 cm to an increase of nearly 45 cm. These average changes are well-supported by sediment volume calculations performed by the USACE as part of hydrographic surveys as well as results of the USGS surveys performed at intermediate time scales (8 months to 45 months). Average bed elevation changes over time for the selected long-term (USACE) cross-channel range lines presented in TM2g (WDNR, 1999c) range from -5.5 to + 5.4 cm/year (see Table 7 of TM2g). These results document the dramatic changes in sediment bed elevations that can occur as the bed of the Lower Fox River is continuously reshaped by the wide range of flows and loads the River experiences.

As a follow-up to TM2g, data for recent hydrographic surveys completed by the USACE were further examined to determine the extent of bed elevation changes. Data for the 1997, 1998, and 1999 surveys were available in a form that permitted calculation of bed elevation changes for all locations surveyed (rather than only at selected locations as shown in TM2g). These results were examined for the portion of the navigation channel from the De Pere to Fort James (Georgia Pacific) turning basins. This portion of the channel has not been dredged since the 1960s so changes in bed elevations reflect the natural channel-forming dynamics of the River. Survey results detailing sediment bed elevation changes between the 1997 and 1999 surveys are presented in Figures 2-5. These data were collected at transect lines positioned every 30 meters (100 feet) along the channel. As reported by the USACE, these surveys provide more than 25,000 individual bed elevation observations for this portion of the channel. Note that a net sediment gain or loss ("burial") rate for a given time period may be estimated from sediment bed elevation change data as the net elevation change over the time between surveys. A summary of results is presented in Table 2-2. These results again document the dramatic changes in sediment bed elevations that can occur as the bed of the Lower Fox River is continuously reshaped by the flows and loads the River experiences. This is further documented by long-term bed elevation data collected by the USACE. Long-term sediment bed elevation profiles along the navigation channel over the period 1977 to 1998 are presented in Figure 2-6. These profiles show that large changes in sediment bed elevation can occur.

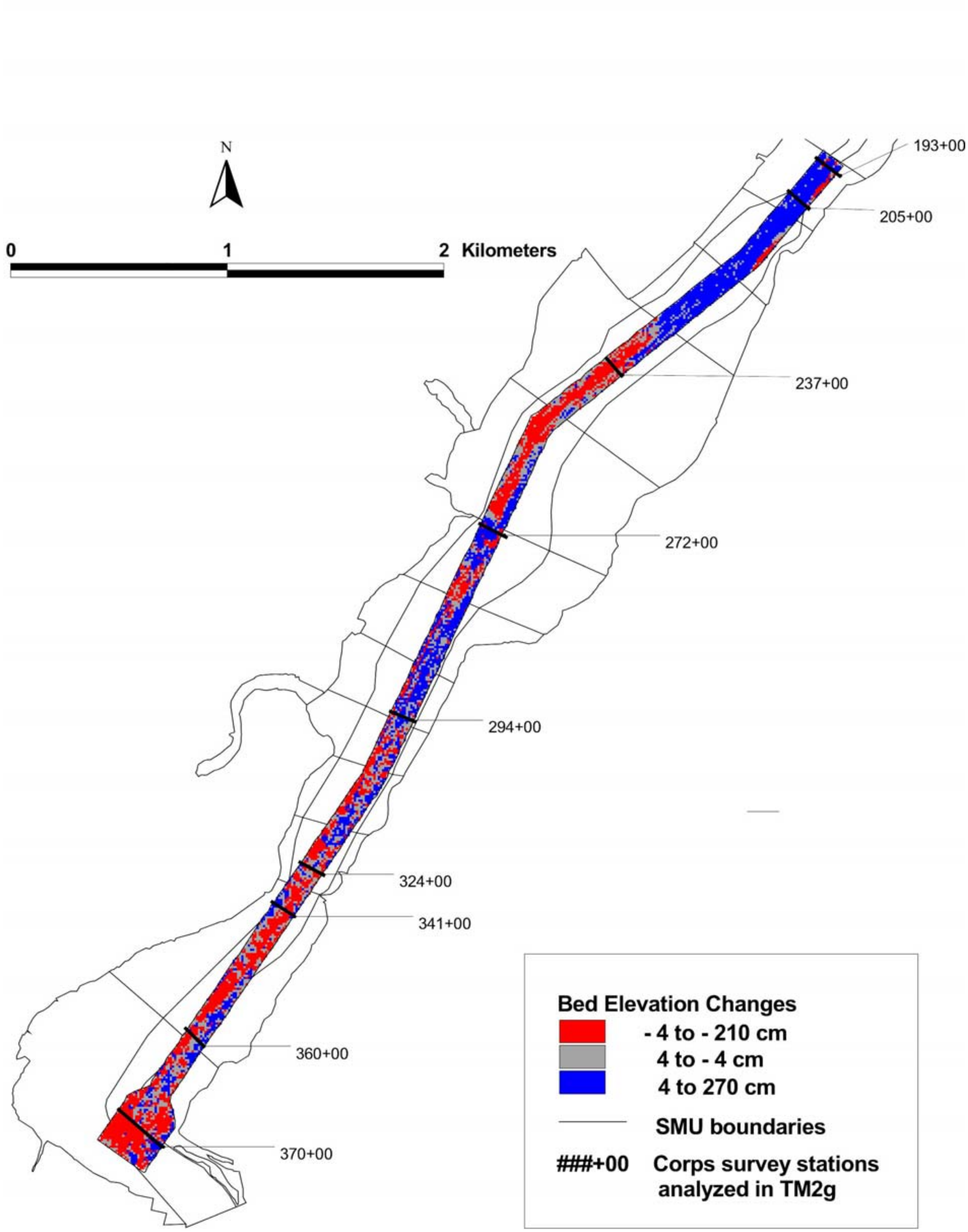

FIGURE 2-5 LOWER FOX RIVER SEDIMENT BED ELEVATION CHANGES: DIFFERENCE BETWEEN 1997 AND 1999 USACE HYDROGRAPHIC SURVEY RESULTS

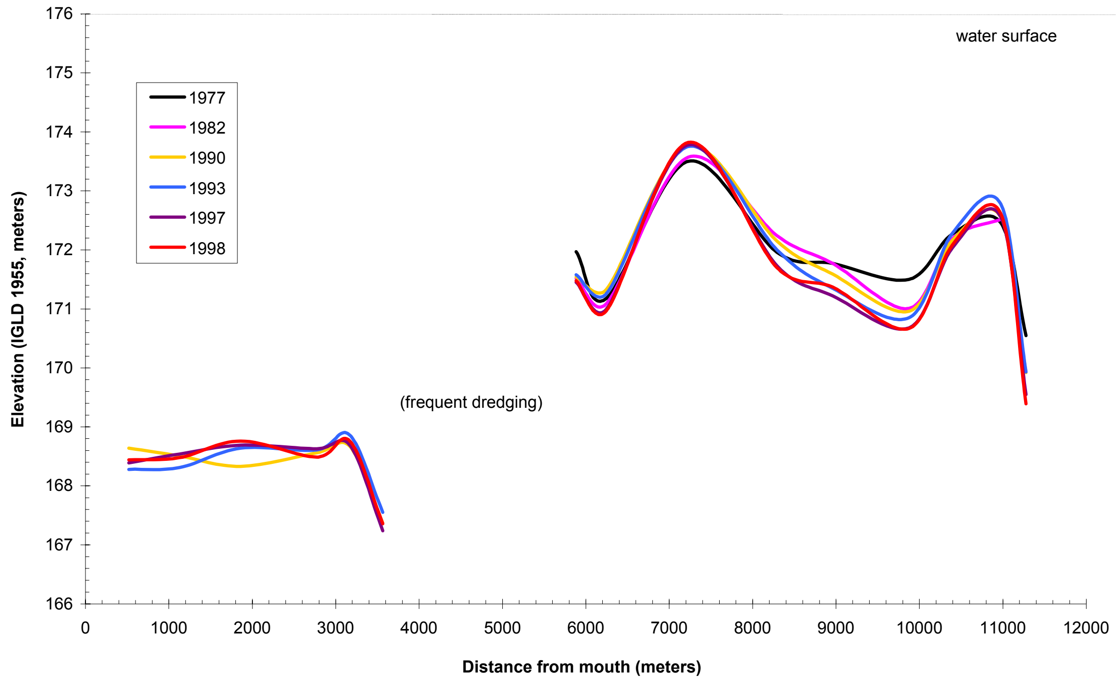

FIGURE 2-6 LOWER FOX RIVER SEDIMENT BED ELEVATION PROFILES: 1977-1998

TABLE 2-2 LOWER FOX RIVER SEDIMENT BED ELEVATION CHANGES, DE PERE TO FORT JAMES (GEORGIA PACIFIC) TURNING BASINS: 1997-1999

Survey Years	Minimum (Maximum decrease at a single point) (cm)	Maximum (Maximum increase at a single point) (cm)	Mean (Average change over all points) (cm)	Volume Change (Cumulative over all points) (m^3)
97-98	- 174	+ 131	+ 6.3	+ 43,717
98-99	- 115	+ 270	- 5.6	- 38,986
97-99	- 209	+ 226	+ 0.7	+ 4,981

These results document that (at least for the 1997-1999 surveys) gross changes in bed elevation at any individual point can be large and differ widely from the net change in elevation in terms of both magnitude and direction. Additionally, a recent study also suggests that portions of the sediment bed downstream of the De Pere dam may be subjected to increased erosion (observed as decreased sediment bed elevations) in response to declining water levels in Green Bay/Lake Michigan. Also note that these data also permit estimation of net rates of sediment accumulation in the River. Net sediment accumulation rates are presented in Section 2.4.

It should be noted that the overall accuracy of the USACE hydrographic surveys was extensively examined. As described by WDNR (1999b, 2001a), the majority of the bed elevation data used for these studies was collected by the USACE as part of Class I surveys. The accuracy of these surveys was confirmed by field tests of the actual combined errors (equipment and procedural) of measurements. Data collected at the Sediment Management Unit (SMU) 56/57 demonstration site in August 1999 indicate that the combined vertical accuracy achieved by the USACE Kewaunee Office was approximately ±4 cm (WDNR, 1999d).

Finally, it is worth noting that in terms of the dynamics of sediment bed elevation changes, the Lower Fox River is not unique. Similar ranges of bed elevation changes have been observed in the Sheboygan River (Wisconsin) (WDNR, 2000a). A recent study of bed mobility in the Sacramento River (California) also demonstrates that the bed of a river can be a very dynamic environment (Dinehart, 2002). In that study, the upper 30 cm of the sediment bed was typically found to be mobile (bedform transport) and moved downstream at rates that ranged from 0.43 to 2.01 m/day (Dinehart, 2002).

In summary, three conclusions may be drawn from these data: (1) large gross increases and decreases in sediment bed elevation can occur at any individual location over time; (2) for broad areas of the River, the net change in sediment bed elevation over time is generally much smaller than the gross changes at individual points; and (3) the sediment bed of the Lower Fox River is not necessarily a stable environment for PCBs because decreases in bed elevation at any point can expose PCBs that were once deeper in the sediment column.

2.4 RATES OF NET SEDIMENT ACCUMULATION

The net rate of sediment accumulation in the Lower Fox River is small. As a consequence, the rate at which PCBs in the sediment bed become isolated from the environment is slow. Rates of net sediment accumulation (net burial rates) were examined by WDNR (2001a). As part of those efforts, net sediment accumulation rates were estimated from a range of information including: (1) sediment bed elevation surveys over time; (2) average depths of maximum PCB concentrations in the sediments and the time since peak discharge; and (3) sediment trap efficiencies and annual sediment budgets. Brief descriptions of these net burial rate estimates follow. More complete descriptions are presented by WDNR (2001a).

The average sediment bed elevation change over a specific time period was used to estimate a net rate of sediment accumulation. From results of the 1997-1999 USACE hydrographic surveys of the River navigation channel between the De Pere and Fort James (Georgia Pacific) turning basins. As noted in Section 2.3, a 0.7 cm increase in average sediment bed elevation occurred over a two-year period in this section of the River. This corresponds to an estimated net burial rate of +0.35 cm/year.

The average depth of maximum PCB concentrations in the sediments column and the time since peak discharge were used to estimate a net rate of sediment accumulation. For samples collected from the River in 1995 (between De Pere and Green Bay), the average depth to maximum PCB concentrations was 24 to 56 cm below the sediment-water interface. Based on TM2d (WDNR, 1999a), the year of peak PCB discharges to the River was 1969. As described in TM2d, note that most PCB discharges to the River occurred prior to implementation of present-day wastewater treatment practices. During the period of peak PCB discharges, loads of point source solids that delivered PCBs to the River were much larger than contemporary loads. Further, the settling characteristics of the particles comprising those loads were substantially different (i.e. untreated versus treated wastes). After accounting for the changing magnitude and characteristics of point source solids over time, the inferred average net burial rate for the 1989 to 1995 period is 0.2 to 1.4 cm/year (WDNR, 2001b).

Sediment trap efficiencies and annual sediment budgets for the River were used to estimate a net rate of sediment accumulation. Using the methods described by Brune (1953) and Dendy (1974), sediment trap efficiencies for the River were estimated to be roughly 10 to 20 percent. Given the total external load of solids to the River, these sediment trap efficiency estimates were used to infer a net burial rate. As estimated from the results of TM2a (FWB2000, 1998), TM2c (LTI, 1999b), TM2d (WDNR, 1999a), and TM3a (WDNR, 2001a), the average total solids load to the Lower Fox River for the period 1989 to 1995 was approximately 146,000 MT/year. With this total load and an overall sediment trap efficiency of roughly 10-20 percent, approximately 14,600-29,200 MT of sediment would be added to the sediment bed annually. Given the total surface area of sediments ($1.19 \times 107\ m^2$) and the average bulk density of sediments in those areas ($5.96 \times 106\ g/m^3$), this corresponds to a net burial rate of approximately 0.21 to 0.42 cm/year.

Note that each of these different methods yields similar net burial rate estimates. Differences in average bed elevation changes over time is the best method for estimating burial rates because it is based on direct observations of the displacement of the sediment-water interface over a given time period. Estimates by other methods are more uncertain. Nonetheless, the 0.2 to 1.4 cm/year rate estimated from the depth of PCB occurrence and the 0.21 to 0.42 cm/year estimated from sediment trap efficiencies are nonetheless in close agreement with the 0.35 cm/yr estimate from bed elevation surveys.

In summary, two conclusions may be drawn from these data: (1) as determined by different approaches, the net rate of sediment accumulation (net burial) in the Lower Fox River is small; and (2) the corresponding rate at which PCBs in the sediment bed become isolated from the environment due to net burial is slow.

2.5 Depths and Rates of Sediment Mixing

Near the sediment-water interface, disturbances of sediments by bioturbation and other events can mix particles (and particle-associated contaminants) within the sediment column. Mixing can cause PCB initially present deeper in the sediment column to return to the sediment surface. The depth to which sediments mix over time in the Lower Fox River is variable. For biological processes, mixing can occur in the top 10 cm of sediment. Other sediment disturbances may mix sediments to much greater depths (as much as 200 cm). Similarly, the rate at which sediments mix is also variable. Depths and rates of sediment mixing in the River were estimated from a range of information including: (1) benthic sediment re-working rates and abundance data; (2) radioisotope data; and (3) sediment bed elevation change data.

Bioturbation can extensively mix sediments (Lee and Schwartz, 1980; McCall and Tevesz, 1982). The depth through which mixing may occur depends on a variety of conditions (pH, dissolved oxygen, temperature, etc.) and the types and abundances (densities) of organisms involved. Benthic community surveys of Lower Fox River sediments indicate that the predominant species of benthic organisms are chironomids and oligochaetes with abundances that range from 500 to 15,000 individuals/m^2 and an average density of approximately 4,500 individuals/m^2 (IPS, 1993a; IPS, 1993b; IPS 2000; WDNR, 1996). Investigations of Great Lakes sediments found that these types of benthic organisms can re-work (mix) sediments to depths of 10 to 20 cm and at rates of 0.33×10^{-5} to 3.66×10^{-5} cm/day/m^2/organism (Matisoff et al. 1999; Matisof and Wang, 2000). This corresponds to sediment mixing rates ranging from 1.72×10^{-10} to 3.81×10^{-9} m^2/s.

Short-term radioisotope tracer studies of Lower Fox River sediments confirm that extensive mixing occurs in the upper sediments. Fitzgerald et al. (2001) examined Beryllium-7 (Be-7) profiles in Lower Fox River sediments. Be-7 is a naturally occurring, short-lived (53-day half-life) radioisotope formed in the upper atmosphere that can be used to determine depths and rates of surface sediment mixing for timeframes between six months to less than one year. Fitzgerald et al. (2001) reported that Be-7 occurred at depths of 5-10 cm in the sediment column. This corresponds to a minimum effective mixing rate of 7.92×10^{-11} to 6.34×10^{-10} m^2/s (5 cm/yr to ~10 cm/0.5 yr). Note that the mixing rate computed from Be-7 observations is similar (within a factor of ~2) to biological mixing rates. It is worth noting on one occasion that detectable Be-7 concentrations were observed in the deepest sample collected. This indicates that for Be-7 both the sediment mixing depth and rate can be greater than the estimated value.

Other processes such as bed elevation changes due to flow events, density currents, and sediment slumping can also disturb and mix sediments. As described in TM2g (WDNR, 1999c) and follow-up efforts (WDNR, 2001a), sediment bed elevations in the Lower Fox River are very dynamic. Over monthly to annual times scales, sediment bed elevations have been observed to regularly fluctuate between 10 to 30 cm. Larger fluctuations of approximately 200 cm have also been recorded over annual time scales. Over broad areas, the net change in bed elevation is very small. This means that at each location where a large decrease in bed elevation occurs, there is typically a nearby location with a correspondingly large increase in elevation. Consequently, within the same general area there is a pattern of mixing where particles and contaminants located deeper within the sediment column can return to the sediment surface and materials initially at the surface are buried until the next disturbance occurs. The mixing depths and rates of such disturbances are highly variable. As noted above, sediment disturbance (mixing) depths of 10 to 30 cm are regularly observed over time frames of roughly one year. This corresponds to mixing rates that range from 3.17×10^{-10} to 2.85×10^{-9} m^2/s.

Long-term radioisotope tracer studies of Lower Fox River sediments confirm that mixing occurs to deeper depths in the sediment column. Steuer et al. (1995) examined Cesium-137 (Cs-137) profiles in Lower Fox River sediments. Cs-137 is a man-made (originating from atmospheric nuclear weapons tests), long-lived (30-year half-life) radioisotope that can be used to estimate depths and rates of sediment mixing for timeframes over the last 40 to 50 years. Steuer et al. (1995) reported that Cs-137 profiles were not interpretable at 15 of 24 locations sampled. At those locations, samples were collected at depths up to 40 cm below the sediment surface. This corresponds to an upper bound for mixing rates at disturbed locations of 1.88×10^{-10} m^2/s.[5] Note that the mixing rate computed from Cs-137 observations is similar (within a factor of ~2) to mixing rates inferred from bed elevation changes.

It is worth noting that sediment disturbances or mixing depths are not uniform throughout the River. However, even at locations where disturbances are less extensive and the sediments preserve interpretable radiotracer profiles, sediment near the sediment-water interface mix over time. LTI (2002) examined Cs-137 profiles in Lower Fox River sediments. LTI (2002) reported that several locations were "not consistently depositional" (i.e. subject to mixing and erosion). Overall, LTI (2002) reported that sediment mixing depths at undisturbed locations ranged from 1 to 20 cm and with an average mixing depth of 6 to 12 cm. Again, these finding are consistent with other estimates of mixing depth.

In summary, four conclusions may be drawn from these data: (1) the typical depths to which sediment mix over time are variable and ranges from 5 to 30 cm; and (2) the maximum depths to which sediment are disturbed over time may be as large as 200 cm; (3) even at locations subject to fewer disturbances, average mixing depths from 6 to 12 cm and maximum mixing depths of 20 cm have been observed; and (4) mixing rates on the order of 1.0×10^{-10} m^2/s occur in the River.

2.6 SUMMARY OF FIELD OBSERVATIONS

The period 1989 to 1995 is the timeframe over which the Lower Fox River was sampled in the most extensive and comprehensive manner. Based on field studies completed over this period, as well as additional studies completed since 1995, observed conditions such as PCB trends in water and surface sediment, sediment bed elevation changes, rates of net sediment accumulation, and depths and rates of sediment mixing specific to Lower Fox River conditions were defined.

Analyses of PCB concentration trends in water indicate that ongoing PCB transport from sediments causes water column PCB levels to increase from essentially zero at the upstream limit of the River to levels that greatly exceed water quality standards throughout the River. Seasonal patterns of low PCB levels during winter months and higher level during summer months exist. However, year-to-year differences in water column PCB levels are not statistically significant, suggesting that concentration changes over time are expected to be slow or near zero.

Analyses of PCB concentration trends in surface sediments indicate that across the entire River a spatial trend of generally decreasing sediment PCB concentrations with distance from Lake Winnebago exists. The trend analyses further indicate that surface sediment PCB concentrations in any reach may increase, decrease, or stay the same over time.

[5] This computation is based on the assumption that complete sediment disturbance occurred to the maximum depth of the samples (~40 cm) over the maximum timeframe for disturbance. The maximum timeframe for disturbance was 27 years as computed as difference between the year of sample collection (1990) and the year of peak Cs-137 fallout (1963).

Across the whole River, the overall rate at which surface sediment PCB concentrations change over time is expected to be slow.

Analyses of sediment bed elevation changes with the Lower Fox River indicate that large gross increases and decreases in bed elevation can occur at any individual location over time. However, for broad areas of the River, the net change in bed elevation over time is generally much smaller than the gross changes at individual points. The large difference between gross and net bed elevation changes indicate that the sediment bed of the River is not necessarily a stable environment for PCBs because decreases in bed elevation at any point can expose PCBs that were once deeper in the sediment column.

Analyses of net sediment accumulation (net burial) rates indicate that recent net burial rates for the Lower Fox River are small. Based on a variety of methods, net burial rates were estimated to be approximately 0.3 cm/yr. As a result of low net burial, the corresponding rate at which PCBs in the sediment bed become isolated from the environment expected to is slow.

Analyses of depths and rates of sediment mixing in the Lower Fox River indicate extensive mixing of sediment can occur and can at time affect the sediment bed to significant depths. Typical depths to which sediments mix over time are variable and range from 5 to 30 cm. The maximum depths to which sediment are disturbed over time may be as large as 200 cm. Even at locations subject to fewer disturbances, average mixing depths from 6 to 12 cm and maximum mixing depths of 20 cm have been observed. Average sediment mixing rates on the order of 1.0×10^{-10} m^2/s are estimated to occur in the River.

3 MODEL DEVELOPMENT HISTORY, ORGANIZATION, AND CALIBRATION

3.1 MODEL DEVELOPMENT HISTORY

The Lower Fox River/Green Bay ecosystem was extensively studied as part of the 1989-90 GBMBS (USEPA 1989; USEPA 1992a,b). As part of the GBMBS, a suite of water quality models describing PCB transport in the Lower Fox River and Green Bay were developed. Two of those models described PCB transport in upstream and downstream portions of the Lower Fox River (Velleux and Endicott, 1994; Steuer et al 1995). Since the end of the GBMBS, efforts to examine and assess the performance of Lower Fox River water quality models have continued. Four generations of model development have been completed. The models calibrated to GBMBS conditions represent the first generation of model development for the River (Steuer et al. 1995; Velleux and Endicott, 1994). The extension of those models to forecast future water quality trends was the second generation of development (Velleux et al. 1995, Velleux et al. 1996). The models used to conduct a post-audit analysis of model performance represent the third generation of development (WDNR, 1997). The model developed as part of RI/FS efforts is the result of continued assessments of Lower Fox River water quality model performance and is the fourth generation of model development. To distinguish it from prior generations of development, this fourth generation model is identified as the "whole" Lower Fox River model (wLFRM).

Development of the wLFRM was based on the results of a 1997 agreement and a peer review of model performance. On January 31, 1997, the State of Wisconsin entered into a Memorandum of Agreement (Agreement) with seven companies that have primary responsibility for PCB discharges to the Lower Fox River. Those seven companies form the Fox River Group (FRG). One component of the Agreement was to "evaluate water quality models for the Lower Fox River and Green Bay." The intent was to establish goals to evaluate the quality of model results. As specified by the Agreement, the Model Evaluation Workgroup (Workgroup) was formed. The Workgroup was comprised of technical representatives for the FRG and WDNR in order to undertake "cooperative and collaborative" evaluations of model performance. Development of a series of technical reports followed. While the model evaluation process was ongoing, the FRG also initiated a peer review of model performance that was managed by the American Geological Institute (AGI, 2000).

The reports developed by the Workgroup were each prepared as a Technical Memorandum (TM). A listing of selected Workgroup TMs is presented in Table 3-1. Each TM listed provides detailed analyses of key aspects of model development such as solids and PCB loads, sediment transport dynamics, and initial conditions. These analyses were designed to take maximum advantage of information from a wide array of sources and were not restricted to the exclusive consideration of information generated during GBMBS or LMMBS data collection efforts. The reports examining solids inputs to the River are of particular importance. Successful simulation of PCB (or any hydrophobic chemical) transport is critically dependent on the transport of the particles with which the contaminant is associated. Given that contemporary point and non-point sources of PCBs to the Lower Fox River are near zero (WDNR, 1999a; LTI 1999a; WDNR, 2001a), it is important to distinguish between solids originating from the watershed (which are essentially free of PCBs) and those originating from the sediment bed (which are PCB contaminated). Those reports (TMs 2a, 2b, 2c, 2d, and 3a) consider solids inputs in much greater detail than was possible during the GBMBS and LMMBS. As described in TM3a (WDNR, 2001a), the Workgroup reports listed in Table 3-1 were the source of the majority of the information necessary for model development.

In addition to Workgroup efforts, additional assessments of model performance were presented by a peer review panel. Among the peer review panel recommendations were (AGI, 2000):

1. Use Lake Winnebago as the upstream limit of the model spatial domain to achieve a zero upstream PCB boundary condition (i.e. a point upstream of the PCB contaminated area);

2. Use a numerical integration scheme that avoids mixing in deep sediments; and

3. Treat solids as (at least) three state variables.

To the greatest extent practical, peer review panel recommendations were integrated into wLFRM development efforts. As recommended by the peer review panel, the wLFRM describes PCB transport in River from Lake Winnebago to the River mouth at Green Bay in a single spatial domain, uses the IPX 2.7.4 framework (USEPA, 2001) to avoid mixing in deep sediments, and treats solids as three state variables throughout the model spatial domain.

It is worth noting that the development history of the wLFRM includes three peer-reviewed journal publications: Velleux and Endicott (1994), Velleux et al. (1995), and Velleux et al. (1996). Note that the IPX 2.7.4 computational framework used for wLFRM simulations was derived from the USEPA WASP series of water quality models. Numerous publications regarding development of the WASP framework exist. Beyond this relationship to the WASP series of models, the development history of the IPX framework was also peer-reviewed by USEPA: Velleux et al. (1994) and USEPA (2001). The USEPA (2001) publication is available via the USEPA National Environmental Publications Internet Site on the world wide web at: http://www.epa.gov/cgi-bin/claritgw?op-Display&document=clserv:ORD:0648. At this time, no other model describing PCB transport in the Lower Fox River is as extensively peer-reviewed.

3.2 MODEL SEGMENTATION AND SPATIAL ORGANIZATION

The full length of the Lower Fox River, from Lake Winnebago to its mouth at Green Bay, was simulated in a single domain. To represent the River in the model framework, this domain was divided into water, surficial sediments, and subsurface sediment layer segments. The optimal choice of segmentation depends on physical characteristics, contaminant concentration gradients, dominant transport processes, and the desired model resolution. Based on these considerations, 40 water column segments and 165 sediment stacks were defined. The sediment stacks were further divided into 165 surface sediment segments, 330 subsurface sediment segments, and 652 deep sediment sections. Groups of segments divide the River into four reaches as presented in Table 3-2. A complete description of wLFRM segmentation is presented by WDNR (2001a).

The physical characteristics of all water column segments (volume, surface area, depth, etc.) were estimated from information presented in National Oceanic and Atmospheric Administration (NOAA) navigation chart number 14916. Additional supporting information was obtained from Lower Fox River hydrographic surveys performed by the U.S. Army Corps of Engineers (USACE) and Ocean Surveys, Inc. (OSI, 1998).

TABLE 3-1 LIST OF SELECTED MODEL EVALUATION WORKGROUP TECHNICAL REPORTS

Report[6]	Title/Topic	Source
Work Plan	Work Plan to Evaluate the Fate and Transport Models for the Fox River and Green Bay	LTI and WDNR (1997)
TM1	Model Evaluation Metrics	LTI and WDNR (1998)
TM2a	Simulation of Historical and Projected Total Suspended Solids Loads and Flows to the Lower Fox River, N.E. Wisconsin with the Soil and Water Assessment Tool (SWAT)	FWB2000 (1998)
TM2b	Computation of Watershed Solids and PCB Load Estimates for Green Bay	LTI (1999a)
TM2c	Computation of Internal Solids Loads in Green Bay and the Lower Fox River	LTI (1999b)
TM2d	Compilation and Estimation of Historical Discharges of Total Suspended Solids and Polychlorinated Biphenyls from Lower Fox River Point Sources	WDNR (1999a)
TM2e	Estimation of Lower Fox River Sediment Bed Properties	WDNR (1999b)
TM2g	Quantification of Lower Fox River Sediment Bed Elevation Dynamics through Direct Observations	WDNR (1999c)
TM3a	Evaluation of Flows, Loads, Initial Conditions, and Boundary Conditions	WDNR (2001a)
TM5b	ECOM-siz-SEDZL Model Application: Lower Fox River Downstream of the De Pere Dam	Baird (2000a)
TM5c	Evaluation of the Hydrodynamics in the Lower Fox River Between Lake Winnebago and De Pere, WI	HQI (2000)
TM “5d”[7]	ECOMSED Model Application: Upstream Lower Fox River from Lake Winnebago to De Pere Dam	Baird (2000b)

6 TM = Technical Memorandum.
7 The designation of this report as TM “5d” is informal based on its relation to companion documents.

TABLE 3-2 LOWER FOX RIVER REACH DEFINITIONS

Reach	Description	Water Segments	Sediment Stacks
1	Little Lake Butte des Morts (Appleton dam)	1-7	1-11, 47-53
2	Appleton to Little Rapids (Little Rapids dam)	8-18	12-37, 54-64
3	Little Rapids to De Pere (De Pere dam)	19-24	38-46, 65-70
4	De Pere to Green Bay (the River mouth)	25-40	71-165

The physical characteristics of all sediment stacks and layers within each stack were estimated from interpolations of field survey results and sediment data collected from 1989 through 1997 as described in TM2e (WDNR, 1999b). Each stack represents one sediment deposit (or sub-deposit division), interdeposit area, or sediment management unit (SMU). These stacks were further divided into 10 vertical layers[8] (to the limit of sediment thickness in any location) as follows, expressed as a distance below the initial position sediment-water interface: 0-5 cm, 5-10 cm, 10-30 cm, 30-50 cm, 50-100 cm, 100-150 cm, 150-200 cm, 200-250 cm, 250-300 cm, and greater than 300 cm. The first three layers in each stack (surface layer and two subsurface layers) were represented as active model segments. Remaining sediments in each stack were represented as deep sediment layers (see USEPA, 2001 for further discussion).

3.3 MODEL PARAMETERIZATION AND CALIBRATION

In addition to the overviews provided in preceding section of this White Paper, the development history, structure, parameterization, and calibration of the wLFRM are described in detail by WDNR (2001a). Simulations for the calibration (and forecast) period were performed using the IPX 2.7.4 framework (USEPA, 2001). The major areas of model parameterization and calibration are: loads, boundary conditions, initial conditions, hydrodynamics (flows), sediment transport, and PCB transport.

Details regarding model parameterization and calibration are well described by WDNR (2001a) and the Technical Memoranda developed by the Workgroup in collaboration with the FRG as listed in Table 3-1. In addition to this extensive documentation, USEPA (2001) presents detailed descriptions of the mathematical formulations for mass transport and transfer processes as implemented in the IPX 2.7.4 framework. A summary of wLFRM features and parameterization is presented in Table 3-3. For convenience, an overview of parameterizations and calibrations for hydrodynamics, sediment transport, and PCB transport follow.

The model calibration period was 1989 to 1995. This period was selected for three reasons. First, the majority of field observations to evaluate model performance are for this timeframe. Second, this period is after improved wastewater treatment practices were implemented and PCB discharges to the River were essentially eliminated. Third, conditions during this period (loads, flows, boundary conditions, etc.) are expected to be representative of future conditions.

[8] TM2e defines nine vertical layers. For wLFRM development, the first layer defined in TM2e (0-10 cm) was subdivided into two layers (0-5 cm and 5-10 cm).

3.3.1 Hydrodynamics

Water flows into the Lower Fox River from several sources: the upstream boundary at Lake Winnebago, tributary streams and direct run-off from the surrounding watershed, and point sources. As described in the model evaluation work plan (LTI and WDNR, 1997), these flow sources were examined as part of TM2a (FWB2000, 1998), TM2d (WDNR, 1999a), and TM3a (WDNR, 2001a). Hydrodynamic models of the Lower Fox River were also developed as part of TM5c (HQI, 2000) and TM5b (Baird, 2000a) to examine the structure of river currents. This information was used to describe the magnitude and temporal dynamics of flows and velocities in the wLFRM.

TABLE 3-3 MODEL FEATURE AND PARAMETERIZATION SUMMARY

Feature	Value	Basis
Spatial Domain	39 Miles (whole River)	Upstream PCB boundary condition is zero; Steuer et al (1995), Velleux and Endicott (1994); WDNR (1997); AGI recommendation (AGI, 2000)
Temporal Domain	1989-1995 (calibration) 100 years (long-term forecast)	TM1 (LTI and WDNR, 1998); period of greatest data availability for calibration
State Variables	3 solids types Total PCBs	Multiple particle types needed to represent transport of different particles; TM2d (WDNR, 1999a); AGI recommendation (AGI, 2000)
Total Segments	535	Steuer et al (1995), Velleux and Endicott (1994); WDNR (1997)
Water Segments	40	Steuer et al (1995), Velleux and Endicott (1994); WDNR (1997)
Surface Sediment Segments	165 (deposits, interdeposits, SMUs)	GBMBS and other field data; WDNR (1997); TM2e (WDNR, 1999b)
Subsurface Sediment Segments	330 (remaining sediment in “deep layers”)	Two layers under each surface segment to permit description of sediment mixing; radioisotope tracer study (Fitzgerald et al. 2001); TM2g (WDNR, 1999c)
Framework	Semi-Lagrangian bed submodel	Avoid mixing in deep sediments; AGI recommendation (AGI, 2000)
Sediment Layers (nominal thickness)	0-5 cm, 5-10 cm, 10-30 cm, 30-50 cm, 50-100 cm, 100-150 cm, 150-200 cm, 200-250 cm, 250-300 cm, 300+ cm	TM2e (WDNR, 1999b); radioisotope tracer study (Fitzgerald et al. 2001) results help define 5 cm surface layer thickness
Flow	Average: 146 m^3/s Range: 29.5 to 667 m^3/s	Observed flow at Rapide Croche extrapolated to include downstream inputs; TM2a (FWB2000, 1998); TM3a (WDNR, 2001a)
Upstream Boundary Loads	Solids: 68,000 MT/year PCBs: 0	Measurements at Lake Winnebago (1986-90); Gustin (1995); Steuer et al (1995); TM3a (WDNR, 2001a)
Watershed Loads	Solids: 54,000 MT/year PCBs: 7.5 kg/year	TM2a (FWB2000, 1998); TM2b (LTI, 1999a), TM3a (WDNR, 2001a)
Internal Loads	Solids: 20,000 MT/year PCBs: not applicable	TM2c (LTI, 1999b)
Point Source Loads	Solids: 4,000 MT/year PCBs: 12.25 kg/year	TM2d (WDNR, 1999a)
Initial Conditions	sand, silt, clay, bulk density, organic carbon, PCBs	TM2e (WDNR, 1999b)

TABLE 3-3 MODEL FEATURE AND PARAMETERIZATION SUMMARY

Feature	Value	Basis
Feature	Value	Basis
Water Velocity	$U_{ij} = F_{LSij}(a\ Q^b)$	TM5c (HQI, 2000), TM5b (Baird, 2000a)
Shear Stress	$\tau = C_f\ \rho U^2$ $C_f \approx 0.003$	TM5c (HQI, 2000), TM5b (Baird, 2000a)
Coarse Settling	V_s = 470 m/day τ_{cd} = 0.80 dynes/cm^2	Gessler (1967); Cheng (1997); force balance
Medium Settling	V_s = 2.15-3.9 m/day τ_{cd} = 0.15 dynes/cm^2	Partheniades (1992); Burban (1990); Chapra (1997)
Fine Settling	V_s = 0.1 m/day τ_{cd} = 0.10 dynes/cm^2	Partheniades (1992); Wetzel (1983); Chapra (1997)
Event Resuspension	Epsilon Equation V_r varies as a function of τ τ_c = 1 dyne/cm^2 $a_0 = 0.75 - 1.5 \times 10^{-3}$ m = 2.3 Z = 1.74	Lick et al. (1995); TM5b (Baird, 2000a); TM5d (Baird, 2000b); Gailani et al. (1991)
"Background" Resuspension	In form of Epsilon Equation V_{rb} varies as a function of τ Average: $V_{rb} \approx$ 0.7 cm/year	interpretation of "fluff" layer resuspension as described by Gailani et al. (1991)
Partitioning	$K_{oc} = 10^{6.3}$ $\nu_x = 9$	GBMBS field data; Velleux and Endicott (1994)
Volatilization	$\ln K_H = 18.53 - 7868/T$ K_L = modified O'Connor-Dobbins K_G = O'Connor/Rathbun	Tateya et al. (1988); Velleux and Endicott (1994)
Sediment Diffusion	$K_f = 2 \times 10^{-8}$ m^2/s ($\approx$ 3.5 cm/day)	After QEA (1999)
Sediment Mixing	$E_M = 1 \times 10^{-10}$ m^2/s	Interpretation of field data; TM2g (WDNR, 1999c)
PCB Biodegradation	$k_B = 0$	McLaughlin (1994)

The velocity at which water moves over the sediment bed surface is the key determinant of the shear stress that is exerted at the sediment-water interface. The shear stress is a controlling factor in the transport of particle-associated contaminants that originate from the sediment bed. The hydrodynamics of the Lower Fox River were examined as part of Workgroup efforts. Technical Memorandum 5c (TM5c) (HQI, 2000) examined hydrodynamics between Lake Winnebago and the De Pere dam. Technical Memorandum 5b (TM5b) (Baird, 2000a) examined hydrodynamics (and sediment transport) between the De Pere dam and the River mouth. For both efforts, two-dimensional hydrodynamic models were constructed and calibrated to available data (flow, water surface elevation, etc.). As described in TM5c and TM5b, the comparison between simulated and observed water surface elevations and flow was excellent. For example, as presented in TM5c regression analyses of the hydrodynamic model results and observed values yielded correlation coefficients greater than or equal to 0.98. This indicates that the hydrodynamic models are appropriate tools for simulating river currents. The hydrodynamic models were then used to develop relationships between the currents the average river flow reported at the Rapide Croche gauging station. These relationships were expressed in the form of a power function as shown in Equation 3.1 of WNDR (2001a).

In general, the correlation between the simulated velocity at each cross-section and observed flow was quite good. With very few exceptions, correlation coefficients (r^2) were generally 0.85 or greater. This indicates that the relationships between flow and velocity are strong. Therefore, especially for long-term simulations, flow can be used to estimate velocity. Hydrodynamic model results were integrated within the wLFRM through use of the relationships defined by regressions with the form of Equation (3.1). For areas downstream of the De Pere dam, velocities at all grid cells within each SMU were averaged prior to regression. Estimates of sediment transport (erosion and deposition fluxes) based on these flow-velocity relationships are described in Section 3.3.2. The parameterization of flow velocity in the wLFRM is well within the range of expected values for this process.

3.3.2 Sediment Transport

Solids enter the Lower Fox River from several sources: the upstream boundary at Lake Winnebago, tributary streams and direct run-off from the surrounding watershed, internal production, point sources, and the sediment bed. As described in the model evaluation work plan (LTI and WDNR, 1997), these solids sources were examined as part of TM2a (FWB2000, 1998), TM2c (LTI, 1999b), TM2d (WDNR, 1999a), TM2e (WDNR, 1999b), and TM3a (WDNR, 2001a). After entering the River, solids and particulate phase chemicals exchange between the water column and the sediment bed as a result of sediment transport processes: resuspension (erosion) and settling (deposition). The shear stress at the sediment-water interface (generated by water flowing over the River bed) is a key determinant of the extent to which materials are incorporated into the bed or are resuspended. Sediment transport models of the Lower Fox River were developed as part of TM5b (Baird, 2000a) and TM5d (Baird, 2000b) to explore interactions between the water column and sediment bed. This information was used to describe sediment transport in the wLFRM.

Suspended solids were simulated as three state variables: coarse, medium, and fine. Total solids is the sum of these three solids classes. Separation of total solids into three classes was based on expected differences in the sediment transport properties of various particulate materials and particle grain size. Note that while grain size is an indicator of solids class, it was not the main determinant. For example, algal particles may have diameters in the silt size range but exhibit quiescent settling speeds far less than those of silts. This parameterization approach is consistent with models developed for other sites such as the Hudson River as well as prior generations of model development for the Lower Fox River.

3.3.2.1 Shear Stresses at the Sediment-Water Interface

As water flows over the sediment bed, shear stresses are generated. The magnitude of these shear stresses is a key determinant in the transport of material between the water column and sediment bed. As described in TM5c (HQI, 2000) and TM5b (Baird, 2000a), shear stresses were computed from water velocities as shown in Equation 3.6 of WDNR (2001a).

In the wLFRM, water velocities were estimated from the flow-velocity relationships computed using hydrodynamic model results as described in Section 3.3.1. Shear stresses were estimated from velocity using Equation 3.6. Water velocity and shear stress functions were computed for the area over each sediment deposit (including sub-deposit divisions), interdeposit, and SMU. The coefficient of friction used for shear stress computations was approximately 0.003 as determined by calibration of the hydrodynamic models presented in TM5c (HQI, 2000), and TM5b (Baird, 2000a). The parameterization of shear stress in the wLFRM is well within the range of expected values for this process.

3.3.2.2 Settling and the Probability of Deposition (Deposition)

Settling velocities and probability of deposition parameters were specified for each of the three particles types simulated. Coarse particles are typically non-cohesive and have settling velocities of hundreds to thousands of meters per day under quiescent conditions depending on particle size (Julien, 1998). In the wLFRM, settling velocities for the coarse size class (~100 µm) were set to 470 m/day using the relationship described by Cheng (1997). Probabilities of deposition were computed using the approach described by Gessler (1967). Medium particles are often cohesive and may flocculate. Floc settling velocities depend on the conditions under which the floc was formed (Burban et al. 1990) and range from 2 to 10 m/day under conditions found in freshwater tributaries. In the wLFRM, settling velocities for the medium size class ranged by season from 2.15 to 3.9 m/day. Fine particles may not extensively flocculate and typically have relatively small settling velocities as a result of their size, shape, density, and other physicochemical properties. For example, clay particles often have negative electrical charges that inhibit flocculation. Other fine particles such as algae generally have mechanisms (such as gas vacuoles) to minimize their settling velocities (Wetzel, 1983). As a result of these attributes and other conditions, fine particles may have near-zero settling velocities. In the wLFRM, settling velocities for the fine size class were set to 0.1 m/day. Probabilities of deposition for medium and fine particles were computed using the approach described by Partheniades (1992). The parameterization of deposition in the wLFRM is well within the range of expected values for this process.

3.3.2.3 Resuspension (Erosion)

The particle resuspension flux was described as a function of the shear stress at the sediment-water interface (Ziegler et al. 1988; Gailani et al. 1991) as described by Equation 3.18 of WDNR (2001a). From the resuspension flux, a resuspension velocity was computed as described by Equation 3.19 of WDNR (2001a).

In the wLFRM, resuspension parameters were selected based on the results of studies of Lower Fox River sediments as reported by Xu (1991) and Lick et al. (1995). The erosion potentials of sediments from twelve locations between the De Pere dam and the River mouth (Reach 4) are presented in Figure 3-1. These measurements were made with the Shaker device. Seven of the twelve samples tested were classified as "soft mud", one sample was classified as "silt," and the remaining four samples were classified as "sandy." As noted by Lick et al. (1995), in the Lower Fox River from the De Pere dam to the East River, the sediments were primarily soft mud. Also as noted, from the East River junction to the mouth of the Lower Fox River, nearshore areas were generally muddy while deeper areas were sandy with pockets of muds. Given the overall predominance of sediments classified as soft mud (and the expected preference of PCBs for such materials due to their greater organic carbon content and particle surface areas), the sediments were assumed to behave as soft mud. The average critical shear stress (τ_c) was assumed to be 1 dyne/cm^2. The sediment resuspension exponent (m) was assumed to equal 2.3. The sediment yield coefficient varied by reach as follows: 1.5×10^{-3} (Reaches 1, 3); 7.5×10^{-4} (Reach 2); and 1.0×10^{-3} (Reach 4). The sediment age constant (Z) was assumed to equal 1.74. Resuspension amounts as a function of shear stress for this parameterization are also presented in Figure 3-1. As shown in Figure 3-1, the parameterization of erosion in the wLFRM is well within the range of field observations.

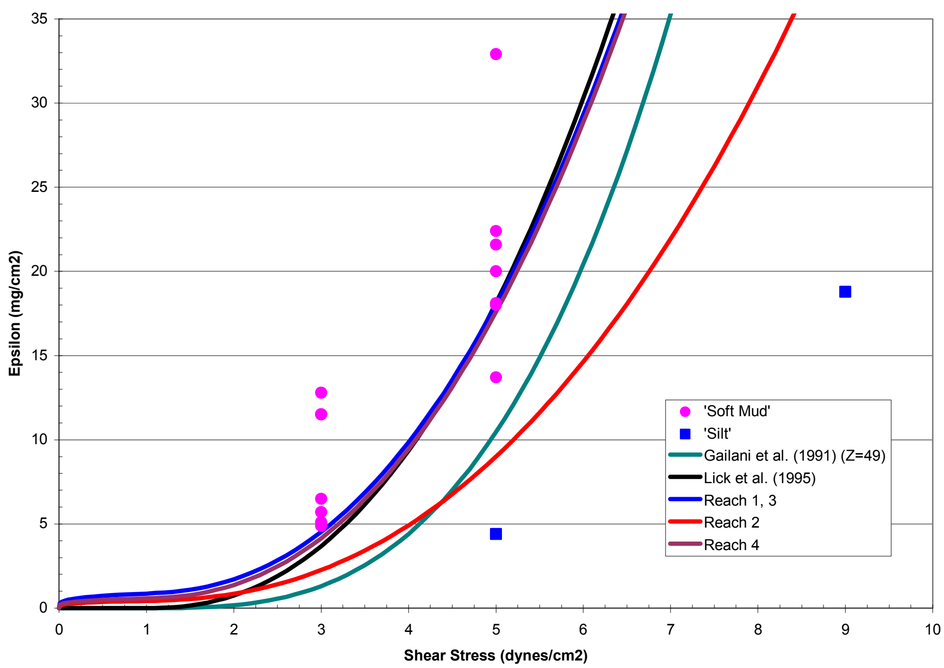

FIGURE 3-1 REPRESENTATION OF EROSION POTENTIALS AS PARAMETERIZED IN THE wLFRM

3.3.2.4 Displacement of the Sediment-Water Interface (Burial and Scour)

When particles are added to or removed from the sediment bed, the vertical position (elevation) of the sediment water interface is displaced relative to a fixed reference location (datum). Addition of particles to the bed causes bed elevation to increase (burial). Removal of particles from the bed causes bed elevations to decrease (scour). Addition of particles to the bed occurs through deposition (settling). Removal of particles occurs through erosion (resuspension). The difference between the fluxes of material entering and leaving the bed defines the direction and magnitude of sediment-water interface displacement.

In the wLFRM, sediment bed elevation changes are computed directly from the difference between the deposition and erosion fluxes for each sediment stack. No parameters to explicitly define the direction or magnitude of sediment-water interface displacements were specified. For each sediment stack, the reference location for displacements was the hard bottom of the sediment column determined from sediment thickness observations as described in TM2e (WDNR, 1999b). Note that no material can ever move into or out of the model network across the hard bottom of the sediment column. Further discussion of this representation of burial and scour is presented in USEPA (2001).

3.3.2.5 Sediment Mixing Processes

As described in Section 2.5, disturbances of sediments by bioturbation and other events can mix particles (and particle-associated contaminants) within the sediment column. Mixing can cause PCB initially present deeper in the sediment column to return to the sediment surface. In the wLFRM, sediment mixing was specified to occur between the top three layers of the sediment column. Typically, this corresponds to mixing depths of 10 to 30 cm. This is consistent mixed layer depths determined from bioturbation, Be-7, and Cs-137, and bed elevation change data as described in Section 2.5. As bed elevations change, the mixing depths can also change. In areas were large bed elevations decreases occur, maximum mixing depths of 75 to 150 cm are possible in the model. This is also consistent observed Cs-17 and bed elevation change data as described in Section 2.5. However, it should be noted that effective mixing depths typically do not exceed the 10 cm (between layers 1 and 2) to 30 cm (between layers 1 and 2) horizons. Sediment mixing coefficients in the wLFRM were set a value of 1.0×10^{-10} m^2/s for the spring, summer and fall months and set to zero for the winter months. This is again consistent with mixing rates determined from bioturbation, Be-7, and Cs-137, and bed elevation change data as described in Section 2.5.

3.3.3 PCB Transport

PCBs can enter the Lower Fox River from several sources (if present in those sources): the upstream boundary at Lake Winnebago, tributary streams and direct run-off from the surrounding watershed, point sources, and the sediment bed. As described in the model evaluation work plan (LTI and WDNR, 1997), these possible PCB sources were examined as part of TM2a (FWB2000, 1998) (see TM3a), TM2d (WDNR, 1999a), TM2e (WDNR, 1999b), and TM3a (WDNR, 2001a). This information was used to describe the magnitude and temporal dynamics of PCB inputs in the wLFRM.

PCBs were simulated as one state variable: total PCBs. Total PCBs represents a family of 209 possible related compounds. Each of these different PCB compounds is known as a congener. Total PCBs is the sum of all congeners present. Consistent with observations, PCB loads from Lake Winnebago were set to zero (WDNR, 2001c). PCB loads from the watershed and point source discharges were set to the values described in TM3a (WDNR, 2001c) and TM2d (WDNR, 1999a). PCB levels in the sediment bed were defined in TM2e (WDNR, 1999b). Parameters for PCB mass transfer processes (partitioning, volatilization, porewater diffusion, etc.) were set to values described by WDNR (2001a) as summarized in Table 3-3. The PCB biodegradation rate was set to zero based on the findings of McLaughlin (1994). Each of these parameterizations is consistent with observed conditions and published literature.

Note that porewater diffusion is one of the possible mass transfer pathways for PCBs in the sediments. This process is included in the conceptual model framework as described by WDNR (2001a). Porewater transfers can move dissolved PCBs between sediment layers and to the water column. In the wLFRM, PCB porewater transfer functions were specified between layers in the sediment column. However, due to an oversight when the model input data file was constructed, the linkage between the surface sediments and the water column was not specified. Note that porewater diffusion can only transport dissolved and bound phase PCBs. Also note that PCBs are strongly associated with particles because they are hydrophobic and that less than 1 percent of the PCBs in the sediments are expected to be associated with dissolved and bound phases. As a result, the impact of this oversight is expected to be very small.

4 wLFRM PERFORMANCE COMPARISON TO OBSERVED TRENDS AND CONDITIONS

Model performance was evaluated by comparing wLFRM results to the observed trends and conditions described in Section 2. The metrics (standards) used to evaluate model performance are described in Section 4.1. Comparisons of model results to observed trends and conditions for water and sediment are presented in Section 4.2. Discussions of a range of factors that affect model performance are then presented in Section 4.3.

4.1 MODEL EVALUATION METRICS

Model evaluation metrics are comparative standards used to assess model performance. Model quality criteria express the idealized level of correspondence between model results and observed conditions. The metrics and quality criteria for this assessment are described in Technical Memorandum 1 (TM1) (LTI and WDNR, 1998). These metrics and criteria were developed jointly by the FRG and WDNR as part of Workgroup efforts to facilitate comparison of model results (output) and observations. The relative difference between model results and observations quantifies model performance and provides an indication of overall model quality. The model quality criteria identified in TM1 was that the mean value of model results for solids and PCBs should be within ±30 percent of observed values in the water column and sediments. The metrics fall into four general categories as shown in Table 4-1. These metrics were used to assess the quality of model results for water and sediments and can be applied to solids or chemicals. Time series metrics were used to compare trends and magnitudes of model results and observations over time at one location. Frequency distribution metrics were used to compare statistical properties. Point-in-time and cumulative performance metrics were used for comparisons over many locations at one point in time or for a specified time period. Specific condition metrics were used to compare model results and observations for specific conditions such as high flow periods or a particular time of year. Further descriptions of these metrics are presented in TM1 (LTI and WDNR, 1998).

TABLE 4-1 TM1 GENERAL CATEGORIES OF MODEL EVALUATION METRICS

Metric Category	Media	Application	Use
Time Series	water	solids, PCBs	Trend and magnitude over time at one location
Frequency Distributions	water, sediment	solids, PCBs	Statistical properties
Point-in-Time/Cumulative Performance: End of period mass balance Sediment bed elevation change Net burial rate (sediment trap efficiency)	water, sediment sediment sediment	PCBs solids solids	Trend and magnitude over many locations at one time or specified time periods
Specific Condition Performance[9]	water	solids, PCBs	Trend and magnitude as functions of river conditions such as flow, time of year, etc.

9 In TM1, this metric category was described as event and non-event concentration and flux comparisons.

4.2 EVALUATION OF MODEL PERFORMANCE

The model calibration period was 1989 to 1995. Simulation results for this period were evaluated according to the metrics and criteria identified in TM1 (LTI and WDNR, 1998). The overall appropriateness of the model is judged by the level of agreement between field observations and simulation results using the model metrics. Evaluations for the water column and sediment are presented in the sections that follow.

4.2.1 Water Column

For the water column, observations exist to permit evaluation for time series, frequency distribution, point-in-time/cumulative performance, and specific condition metrics. Time series and frequency distribution comparisons of observations and model results were developed for each of the five River monitoring stations: Appleton, Kaukauna, Little Rapids, De Pere, and the River mouth. Model performance assessments for these metrics at the Appleton and River mouth stations are presented in Figures 4-1 through 4-8. Comparisons at the other monitoring stations are presented in WDNR (2001a). The time series comparisons indicate that model results agree with the trend and magnitude of observations. However, the results are generally less than observed values indicating that the model has a low bias. Note that model results are also less than the maximum observed values. Model results are nonetheless in satisfactory agreement with observed values and meet the ±30 percent quality criteria established in TM1 based on frequency distribution comparisons. A summary of calibration simulation performance for solids and PCBs in the water column based on frequency distribution comparisons is presented in Table 4-2.

Cumulative performance comparisons were developed for the River mouth monitoring station at Green Bay. The USGS estimated PCB export to Green Bay for 1989 and 1990 (House et al. 1993) and also for 1994 and 1995 (USGS, 1999). Comparisons of USGS PCB export estimates and model results for these two time periods are presented in Figure 4-9 and 4-10. Overall, model results are about 27 percent less than the USGS estimates. This again indicates that the model has a low bias. Model results are nonetheless in satisfactory agreement with USGS estimates and meet the ±30 percent quality criteria established in TM1 based on these cumulative performance comparisons. A summary calibration simulation performance for PCBs in the water column based on cumulative PCB export comparisons is presented in Table 4-3.

TABLE 4-2 FREQUENCY DISTRIBUTION COMPARISONS FOR THE WATER COLUMN

Constituent	Relative Difference Between Mean Observed and Modeled Concentrations by Monitoring Site						
	Appleton	Kaukauna	Little Rapids	De Pere	River Mouth	Average (All Sites)	Average (4 sites)[10]
TSS	-19.5%	-13.5%	-8.6%	-5.8%	-32.4%	-16.0%	-17.8%
PCBs	-40.5%	-31.0%	-73.3%	-31.0%	-16.8%	-38.5%	-29.8%

10 Average of four sites: Appleton, Kaukauna, De Pere, and the river mouth.

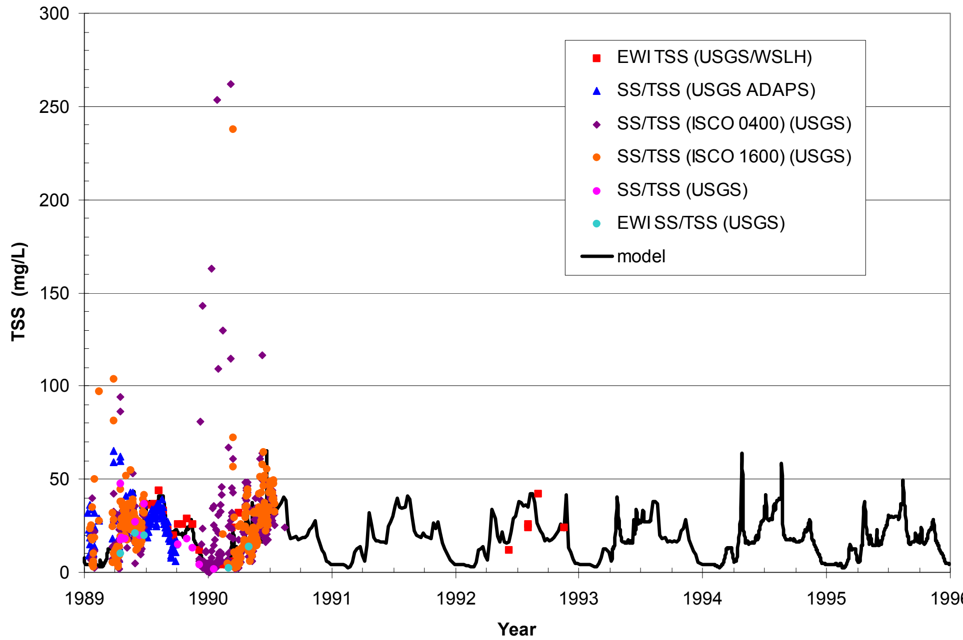

FIGURE 4-1 TIME SERIES OF WATER COLUMN SOLIDS CONCENTRATIONS AT APPLETON: 1989-1995

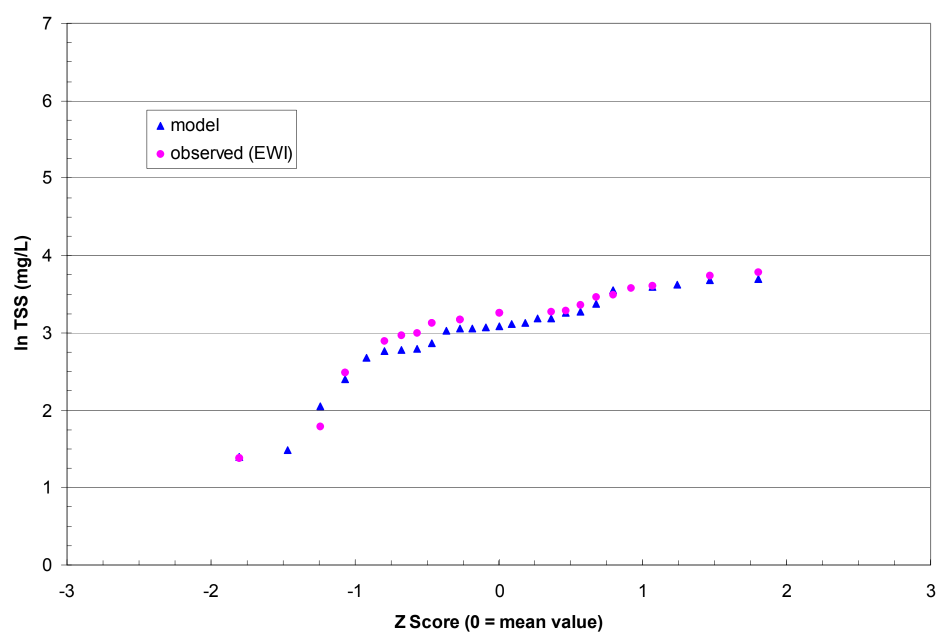

FIGURE 4-2 FREQUENCY DISTRIBUTIONS OF WATER COLUMN SOLIDS CONCENTRATIONS AT APPLETON: 1989-1995

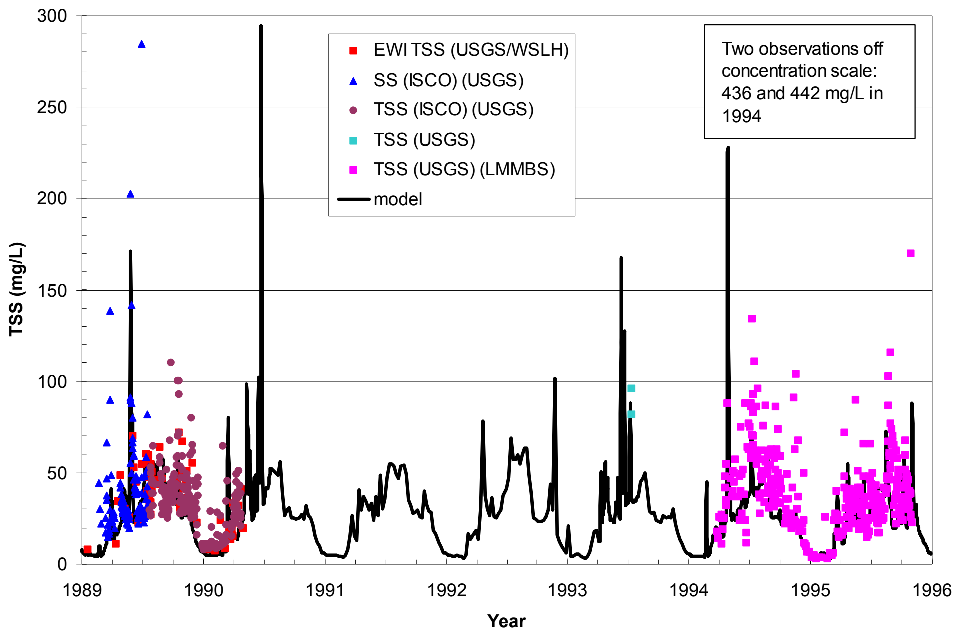

FIGURE 4-3 TIME SERIES OF WATER COLUMN SOLIDS CONCENTRATIONS AT THE RIVER MOUTH: 1989-1995

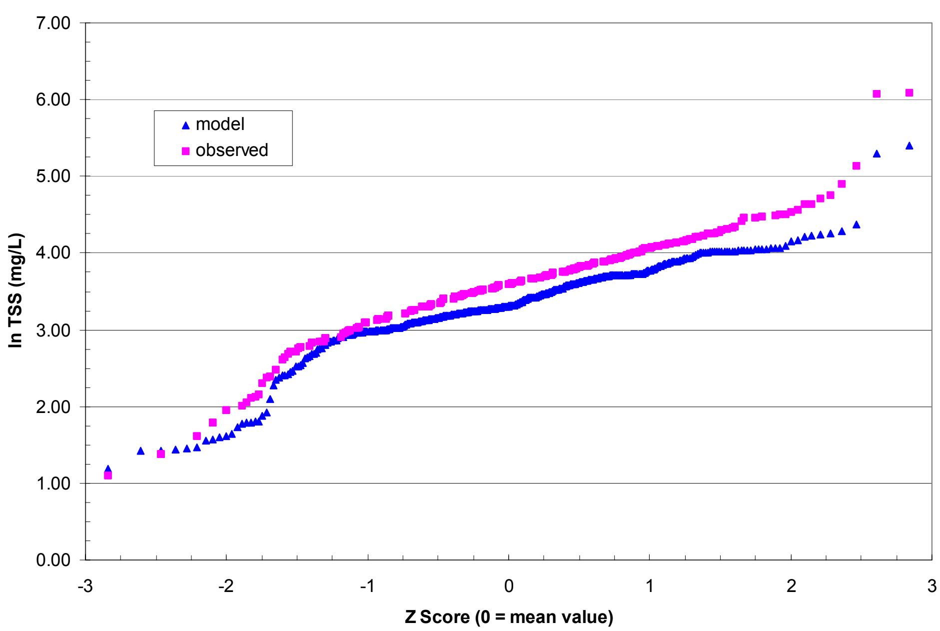

FIGURE 4-4 FREQUENCY DISTRIBUTIONS OF WATER COLUMN SOLIDS CONCENTRATIONS AT THE RIVER MOUTH: 1989-1995

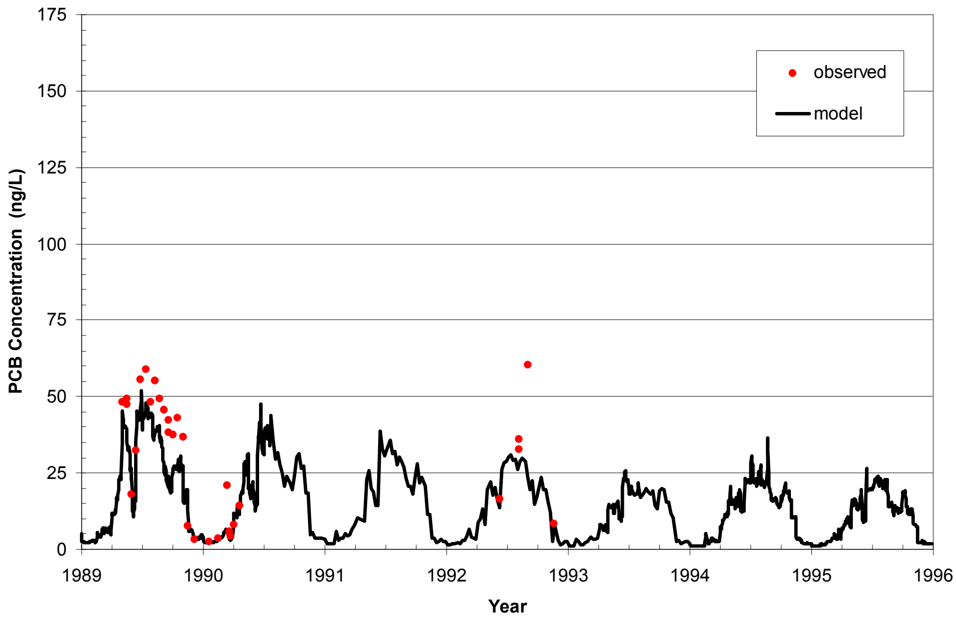

FIGURE 4-5 TIME SERIES OF WATER COLUMN TOTAL PCB CONCENTRATIONS AT APPLETON: 1989-1995

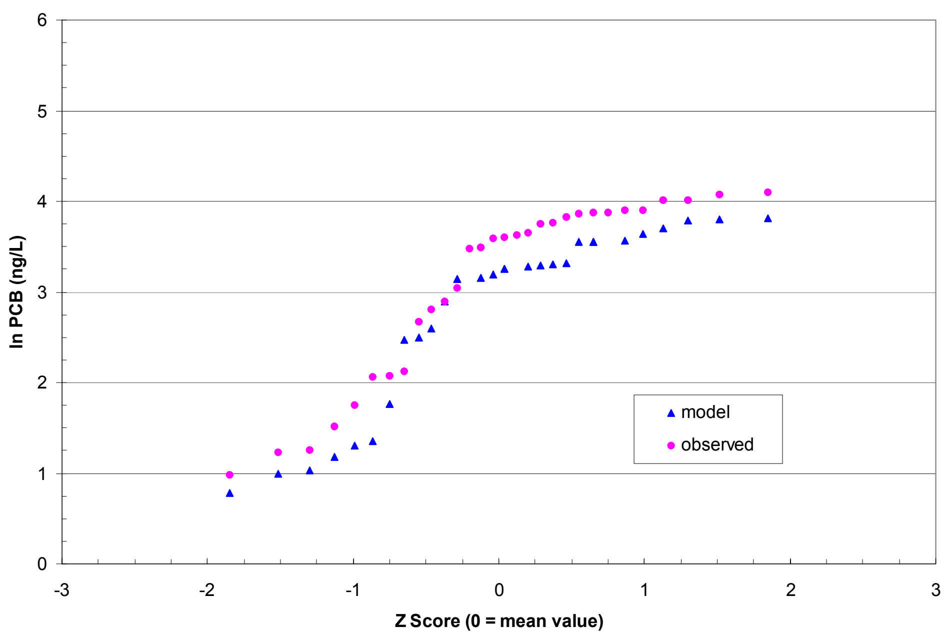

FIGURE 4-6 FREQUENCY DISTRIBUTIONS OF WATER COLUMN TOTAL PCB CONCENTRATIONS AT APPLETON: 1989-1995

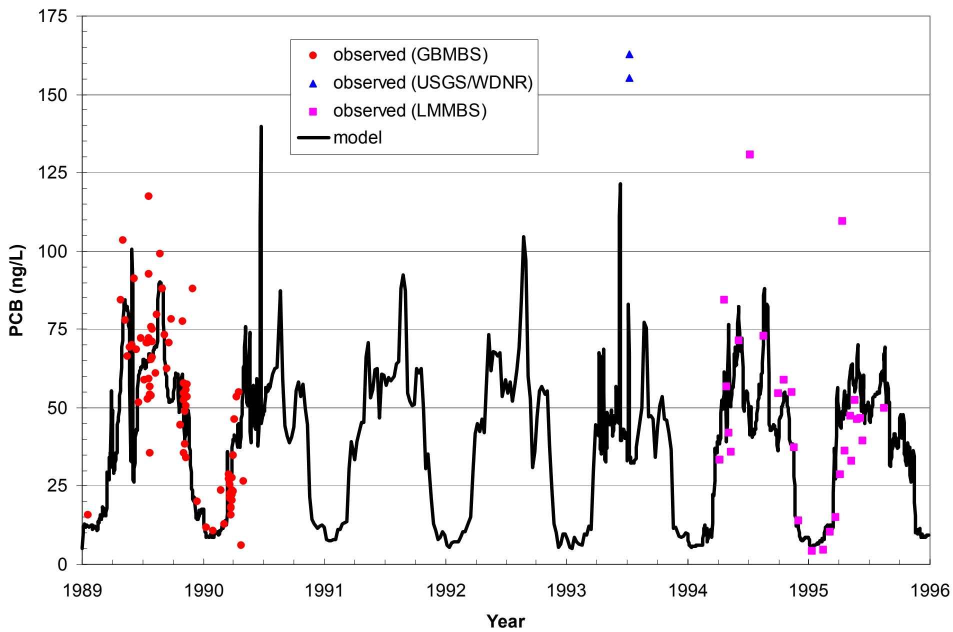

FIGURE 4-7 TIME SERIES OF WATER COLUMN TOTAL PCB CONCENTRATIONS AT THE RIVER MOUTH: 1989-1995

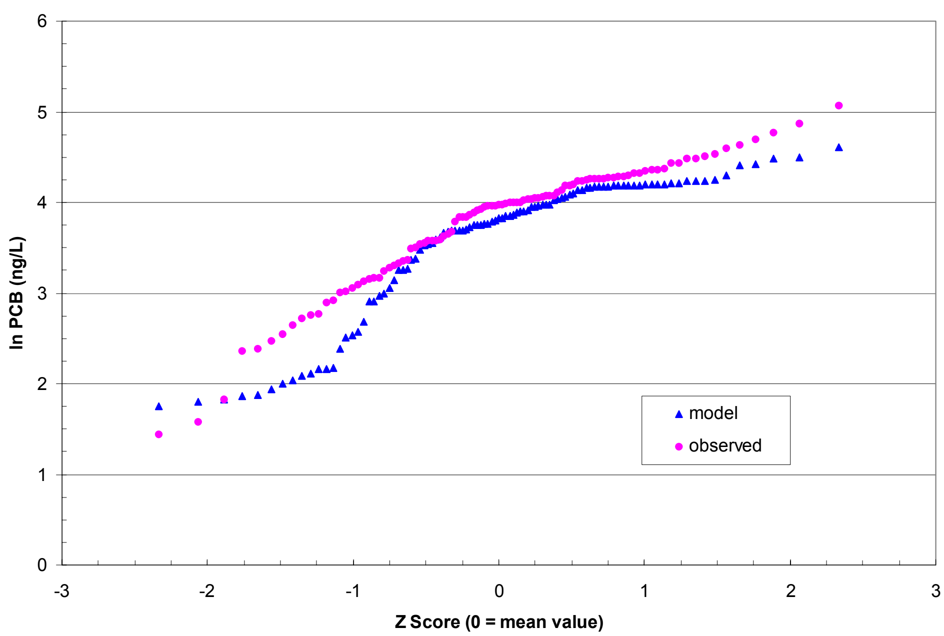

FIGURE 4-8 FREQUENCY DISTRIBUTIONS OF WATER COLUMN TOTAL PCB CONCENTRATIONS AT THE RIVER MOUTH: 1989-1995

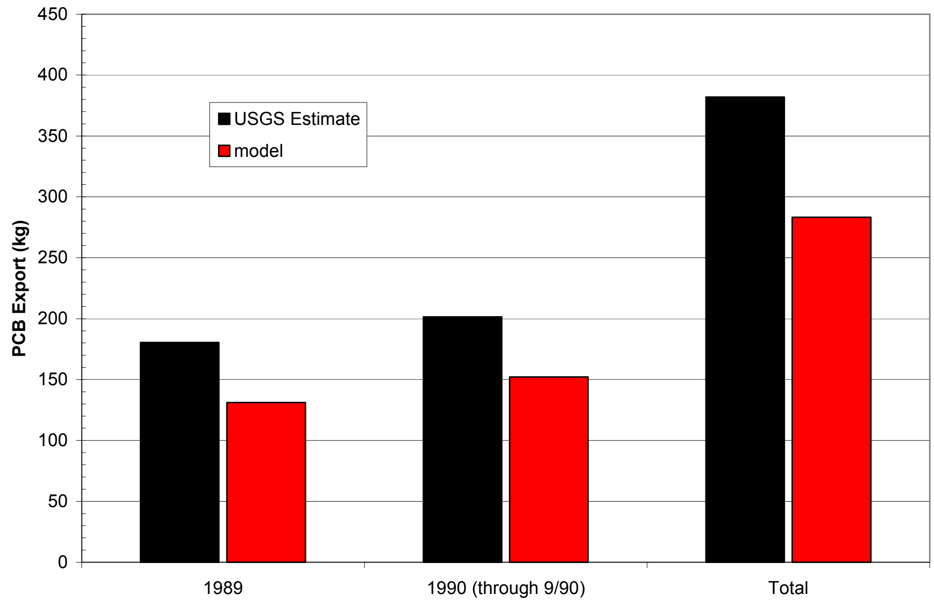

FIGURE 4-9 COMPARISON OF CUMULATIVE PCB EXPORT TO GREEN BAY: 1989-1990

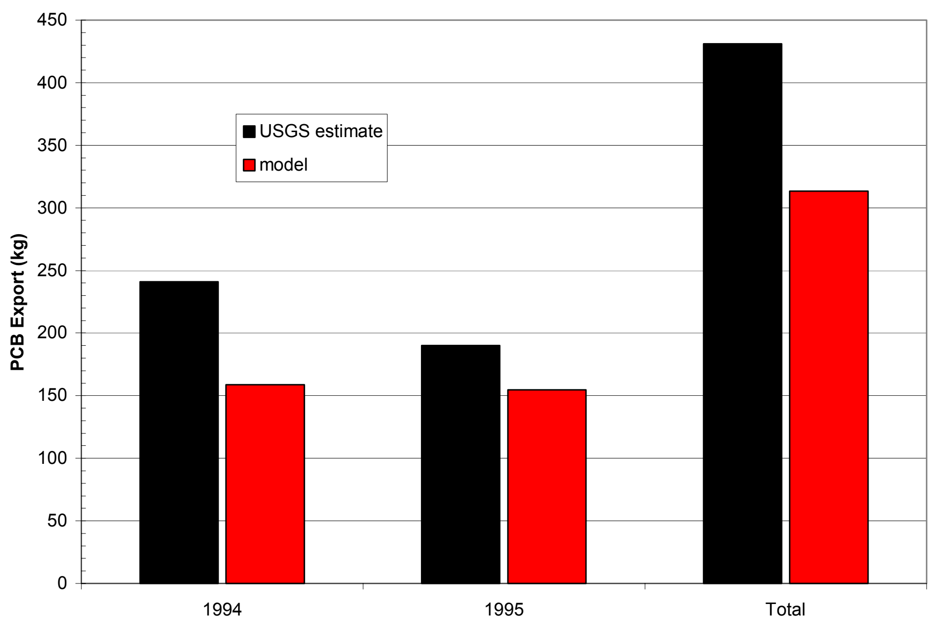

FIGURE 4-10 COMPARISON OF CUMULATIVE PCB EXPORT TO GREEN BAY: 1994-1995

TABLE 4-3 COMPARISON OF CUMULATIVE PCB EXPORT TO GREEN BAY: 1989-1990

Time Period	wLFRM PCB Export (kg)	USGS Estimated PCB Export (kg)	Difference (%)
1989 (1/1 - 12/31)	131	180	-27.4
1990 (1/1 - 9/30)	152	201	-24.5
Total (1/1/89 - 9/30/90)	*283*	*381*	*-25.9*
1994 (1/1 - 12/31)	159	241	-34.0
1995 (1/1 – 12/31)	155	190	-18.4
Total (1/1/94 - 12/31/95)	*314*	*431*	*-27.1*
Cumulative Total	**597**	**812**	**-26.5**

TABLE 4-4 SPECIFIC CONDITION COMPARISONS FOR THE WATER COLUMN

Constituent	Mean Relative Difference Between Observed and Model Concentrations by Monitoring Site[11]						
	Appleton	Kaukauna	Little Rapids	De Pere	River Mouth	Average (All Sites)	Average (4 sites)
TSS	-2.0%	-2.2%	-6.5%	1.0%	-1.8%	-1.5%	-0.1%
PCBs	18.0%	2.4%	46.7%	-18.0%	20.7%	14.0%	5.8%

Specific condition (concentration-flow) comparisons of observations and model results were developed for each of the five River monitoring stations: Appleton, Kaukauna, Little Rapids, De Pere, and the River mouth at Green Bay. Model performance assessments for these metrics at the Appleton and River mouth stations are presented in Figures 4-11 through 4-14. Comparisons at the other monitoring stations are presented in WDNR (2001a). At all five monitoring stations, water column solids and PCB observations exist for a wide range of flows. In general, the comparisons indicate that model results agree with the trend and magnitude of the observations. However, it is worth noting that model results are often less than observed values at flows greater than 200 m^3/s. This again indicates that the model has a low bias. Model results are nonetheless in satisfactory agreement with observed values and meet the ±30 percent quality criteria established in TM1 based on these specific condition comparisons. A summary of calibration simulation performance for solids and PCBs in the water column based on specific condition performance comparisons is presented in Table 4-4.

11 Differences computed from signed errors. Across the range of flows, errors offset each other. Average root mean square (RMS) errors (relative to the mean) were much larger: 42.6 percent for solids and 65.8 percent for PCBs. However, note that RMS errors can be sensitive to a few large differences between simulated and observed values.

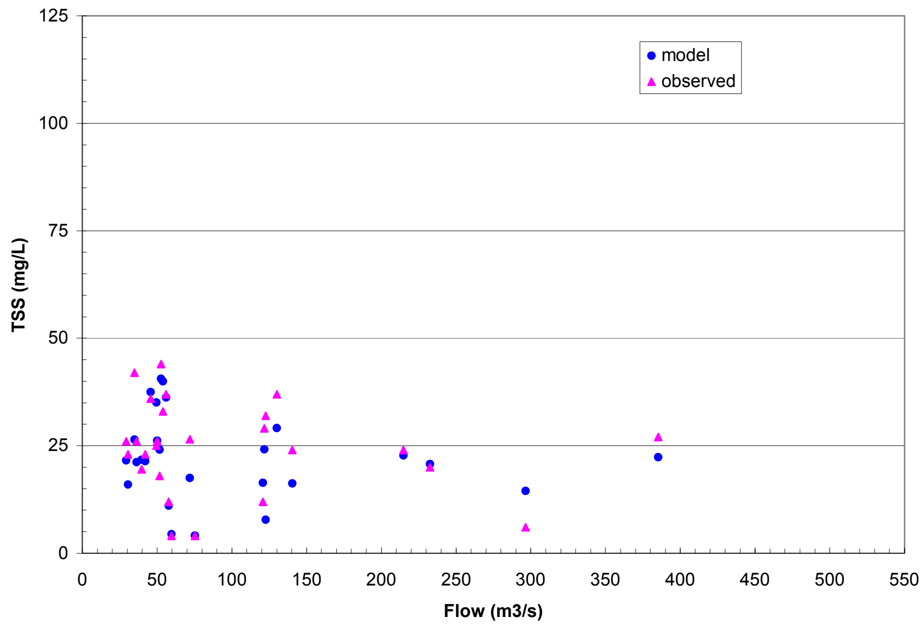

FIGURE 4-11 WATER COLUMN TSS CONCENTRATION VERSUS RIVER FLOW AT APPLETON: 1989-1995

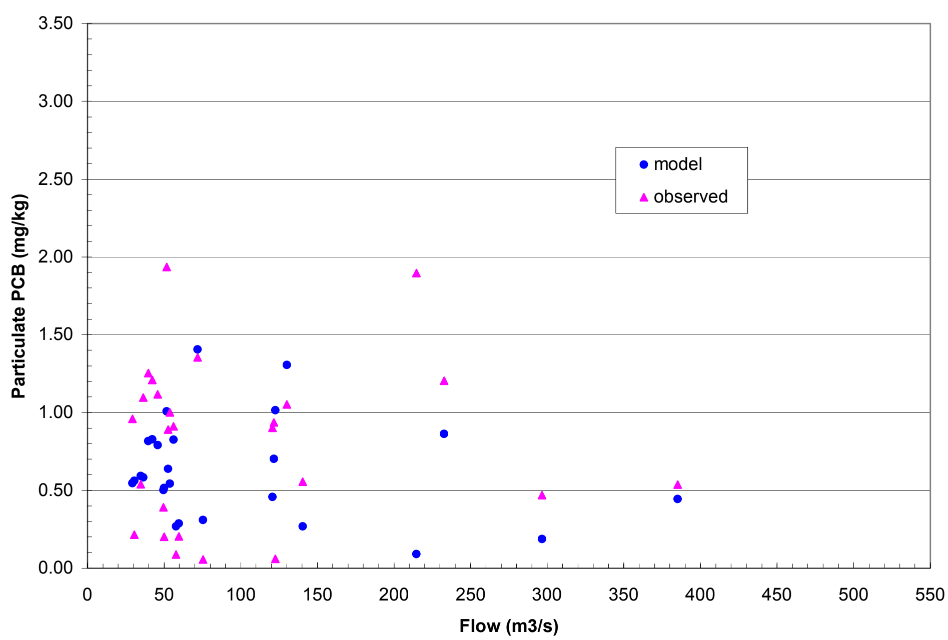

FIGURE 4-12 WATER COLUMN PARTICLE-ASSOCIATED PCB CONCENTRATION VERSUS RIVER FLOW AT APPLETON: 1989-1995

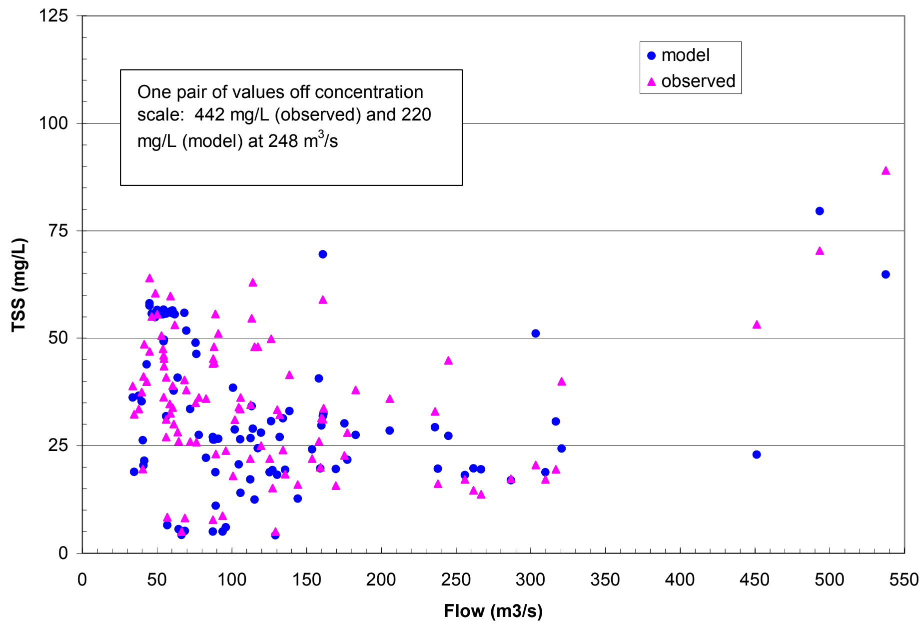

FIGURE 4-13 WATER COLUMN TSS CONCENTRATION VERSUS RIVER FLOW AT THE RIVER MOUTH: 1989-1995

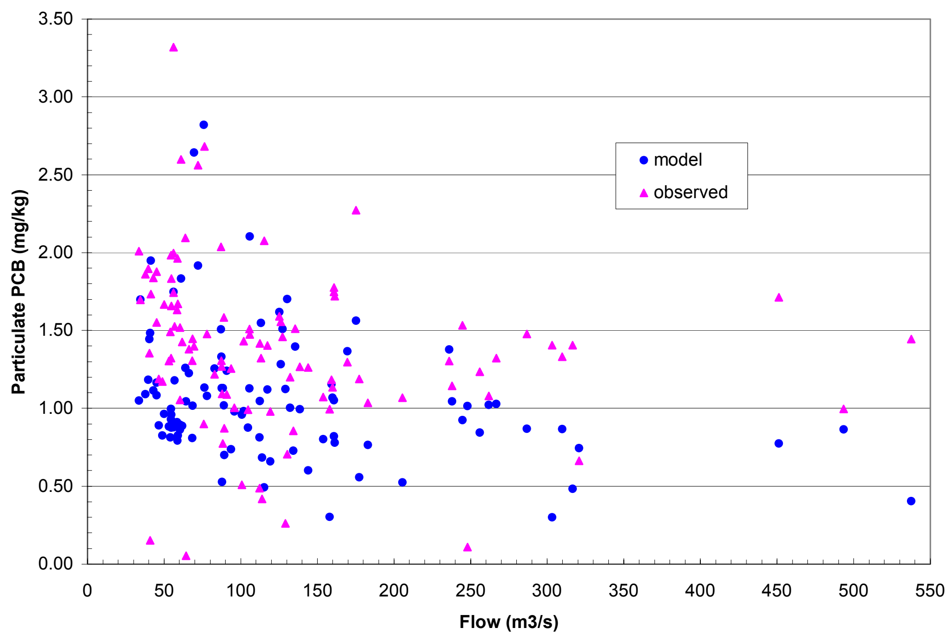

FIGURE 4-14 WATER COLUMN PARTICLE-ASSOCIATED PCB CONCENTRATION VERSUS RIVER FLOW AT THE RIVER MOUTH: 1989-1995

4.2.2 Sediments

For sediments, observations or inferences exist to permit evaluation for point-in-time/cumulative performance metrics. Evaluations can be constructed to examine sediment bed elevation changes, net sediment burial rates and trap efficiencies, and sediment PCB concentration trends. Model performance assessments relative to these metrics are presented in the sections that follow.

4.2.2.1 Sediment Bed Elevation Change Comparisons

Cumulative performance comparisons of observed sediment bed elevation changes and model results were developed for a series of hydrographic survey stations and station groups presented in TM2g (WDNR, 1999c): T10; 370+00, 360+00, and T9; 205+00 and T5; 91+00; and 61+00 and T3. As most bed elevation data are restricted to the River navigation channel, most of the stations selected for comparisons are located between the De Pere dam and the River mouth. Station T10 is located just upstream of the De Pere dam in the area of Deposits GG and HH. Stations 370+00, 360+00, and T9 are located just downstream of the De Pere dam in the area of SMUs 20-25. Stations 205+00 and T5 are located approximately 3.9 miles (6.2 km) upstream of the River mouth near the Fort James (Georgia Pacific) West mill in the area of SMUs 50-55. Station 91+00 is located just upstream of the East River turning basin, approximately 1.7 miles (2.8 km) upstream of the River mouth, in the area of SMUs 86-91. Stations 61+00 and T3 are located just downstream of the East River turning basin, approximately 1.2 miles (1.8 km) upstream of the River mouth, in the area of SMUs 92-97. Comparisons of sediment bed elevation changes are presented in Table 4-5.

In general, model results can differ from observed values. For the comparisons in Table 4-5, model results are 83 percent less than the observations on average. For many of the locations and time periods examined, the results may match the direction of the observations (increase or decrease) but differ in scale. For other locations and times, results differ from observations in terms of both direction and scale. However, it is important to consider the nature of the observations and results. Observed values represent conditions along a line. USACE hydrographic surveys demonstrate that bed elevations along a line can differ widely from station to station. In contrast, model results represent average conditions for large areas. Given the wide station-to-station variations, the average elevation across a large area can be distinctly different than the average elevation along an individual transect line. Consequently, comparisons between these observations and model results may not indicate the quality of model performance.

More importantly, significant differences between the scales of observed bed elevation changes and model results are expected. As described in TM5b (Baird, 2000a) and TM5d (Baird, 2000b), the underlying sediment transport models on which the wLFRM is based do not capture the scale of observed bed elevation changes. Moreover, no sediment transport model ever developed for this Site to date has been able to capture the range of observed bed elevation changes over time. As a consequence of the limitations of the underlying sediment transport models, the wLFRM does not represent the full range of observed sediment bed elevation changes over time. Further discussion of these issues is presented in Section 5.

TABLE 4-5 COMPARISON OF SEDIMENT BED ELEVATION CHANGES

Station (Agency)	Time Period	Observed (cm)	Model (cm)[12]
T10 (USEPA)	May 1994 to November 1994 November 1994 to August 1995	-9 -5	-0.09 +0.01
370+00 - 360+00 (USACE)	1990 to 1993 1993 to 1997	-3.5 -15	-1.26 -0.11
T9 (USEPA)	May 1994 to November 1994 November 1994 to August 1995	+10 -6	+0.31 -0.27
205+00 (USACE)	1990 to 1993 1993 to 1997	-7 -26	-0.74 ~0 (-0.002)
T5 (USEPA)	May 1994 to July 1994 July 1994 to November 1994 November 1994 to August 1995	+1 -7 +19	-0.02 +0.04 -0.06
91+00 (USACE)	1990 to 1993 1993 to 1997	+5 +2	+1.3 +0.62
61+00 (USACE)	1990 to 1993 1993 to 1997	+5 +7	+7.0 +2.8
T3 (USEPA)	May 1994 to September 1994 September 1994 to November 1994 November 1994 to August 1995	+72 -94 +14	+0.26 +0.03 +1.04

4.2.2.2 Net Burial Rate Comparisons

Cumulative performance comparisons of estimated and inferred net burial rates and model results were developed. One net burial rate value was estimated from results of the 1997-1999 USACE hydrographic surveys of the River navigation channel between the De Pere and Fort James (Georgia Pacific) turning basins. As noted in Section 4.2.2.1, in this section of the River, a 0.7 cm increase in average sediment bed elevations occurred over a two year period. This corresponds to an estimated net burial rate of +0.35 cm/year. A second net burial rate value was inferred from the depth of maximum PCB concentrations in River sediment samples collected in 1995 between De Pere and Green Bay. Based on TM2d (WDNR, 1999a) the year of peak PCB loads to the River was 1969. Based on the 1995 samples, the average depth to maximum PCB concentrations was 24 to 56 cm below the sediment-water interface. This corresponds to an inferred average net burial rate of approximately 1-2 cm/year for the period 1969-1995. However, also as described in TM2d, it is important to note that most of the PCB discharge to the River occurred prior to the implementation of present-day wastewater treatment practices. During the period of peak PCB discharges, loads of point source solids that delivered PCBs to the River were much larger than contemporary loads. Further, the settling characteristics of the particles comprising those loads were substantially different (i.e. untreated versus treated wastes). Consequently the net burial rate of PCBs was likely very high in the past and much smaller in recent years. When adjusted for the changing magnitude and characteristics of point source solids and indexed to the 1989-1995 period, the inferred average net burial rate is approximately 0.2 to 1.4 cm/year (WDNR, 2001b). Comparisons of net burial rates are presented in Table 4-6.

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12 Model results are computed through 1995. Comparisons to observed values through 1997 are qualitative.

TABLE 4-6 COMPARISON OF NET BURIAL RATES

Reach	1	2	3	4	Average
Range of Estimates/Inferences	+0.35 cm/year (estimated from observed bed elevations changes USACE 1997-1999) +0.21 to + 0.42 cm/year (estimated from loads and sediment trap efficiencies) +0.2 to +1.4 cm/year (inferred from PCB depth in sediment, indexed to 1989-1995)				
Model	+0.43 cm/year	-0.03 cm/year	+0.25 cm/year	+0.12 cm/year	+0.22 cm/year

In general, model results are within the range of estimated and inferred net burial rates. Note that results for Reach 2 differ the most from the estimated and inferred net burial rates. Reach 2 is narrow and fast moving compared to other sections of the River. Therefore, the near zero net burial rate (in fact a small net scour rate) for this reach is an expected result. However, further performance assessments using this metric were difficult to develop for numerous reasons. The estimated and inferred burial rates are based on observations collected between De Pere and Green Bay. As presented in TM2g (WDNR, 1999c), bed elevation changes (and therefore net burial rates) vary widely in space and over time. The estimate rate of +0.35 cm/year was computed for 1997-1999. The rate applicable to 1989-1995 in each reach may be different. Further, even after accounting for differences in point source loads and particle deposition characteristics, the net burial rate inferred from the depths of maximum PCB concentrations in the sediment is based on values for individual locations. At each location, the inferred rate can vary widely. Extrapolations from single locations to broad areas may be inaccurate. Further discussion of these issues is presented in Section 5.

4.2.2.3 Surface Sediment PCB Concentration Trend Comparisons

Cumulative performance comparisons of inferred annual surface sediment PCB concentration trends and model results were developed for each River reach as well as the whole River. Inferred trends were developed from field observations aggregated to represent the 0-10 cm sediment layer as described in Appendix B and summarized in Section 4.2.2.2. Model results were also aggregated to represent the 0-10 cm layer for each sediment stack (volume-weighted average in the vertical) and then averaged for each reach or the whole River (area-weighted average in the horizontal). Comparisons of annual surface sediment PCB concentration trends are presented in Table 4-7.

Results for Reach 1 agree with the direction of the inferred trend but are smaller in scale. Results for Reach 2 differ in both direction and scale. However, inferred trends over time for these two reaches may actually reflect PCB concentration trends in space due to changes in sampling locations over time. Results for Reach 3 agree with both the direction and scale of the inferred trend and are near zero. This is consistent with the inference that no significant PCB concentration trends over time exist in Reach 3. Results for Reach 4 also agree with the direction of the inferred trend but are slightly larger in scale. Overall model results fall just outside of the lower range of inferred trends.

TABLE 4-7 COMPARISON OF ANNUAL SURFACE SEDIMENT (0-10 CM) PCB CONCENTRATION TRENDS

Reach	1	2	3	4	All
Inferred	-11.1% to -37.9%	+15.4% to +84.0%	-25.4% to +6.4%	-8.5% to +9.1%	+0.6% to +13.8%
Model	-6.8%	-5.8%	-1.2%	+9.6%	-1.0%

When considering these comparisons, it is important to recall the numerous caveats associated with inferred surface sediment PCB concentration trends. Apparent trends over time may be strongly influenced by, or reflect, spatial heterogeneity and analytical bias. As a consequence, it is difficult to determine direction or scale of any potential trend from these data. Because apparent trends may really reflect shifts in sampling locations over time or differences in analytical procedures, the uncertainty associated with these trend inferences is very high. As a result, comparisons to these sediment PCB concentrations trend inferences may not indicate the quality of model performance. Further discussion is presented in Section 5.

5 DISCUSSION

5.1 APPROPRIATENESS OF THE wLFRM FOR USE IN THE RI/FS, THE PROPOSED PLAN, AND ROD

WDNR believes the wLFRM is appropriate for its use within the RI/FS. As described in Sections 2 through 4 of this White Paper, as well as by WDNR (2001a), the Technical Memoranda developed by the Model Evaluation Workgroup, and other supporting documents, the wLFRM successfully represents the observed trends of PCB in the water column and sediment bed of the Lower Fox River. Model parameter values are well within the range of observed values for each transport process in the model. Model performance is also generally within the limits specified by the model evaluation metrics developed in collaboration with the FRG and documented in TM1 (LTI and WDNR, 1998).

Development of the wLFRM is consistent with the information developed by the Workgroup. The wLFRM was developed collaboratively through multiple governmental, university, and industry workgroups. The development history of the model framework and its application to the Lower Fox River has been extensively documented as described in Section 3.1 of this White Paper. In particular, wLFRM was based on the findings of the Model Evaluation Workgroup Technical Memoranda prepared in collaboration with the Fox River Group (FRG) of Companies on the basis of a January 1997 Agreement. The Technical Memoranda define values for critical model features such as flows, loads, initial conditions, boundary conditions, and sediment transport. The Workgroup reports listed in Table 3-1 represent the most detailed description possible of pertinent River conditions using existing data and provided the majority of the information necessary for model development.

Further, development of the wLFRM is consistent with peer-reviewed journal publications and is also consistent with the recommendations of a peer review panel. The wLFRM and IPX 2.7.4 framework have been thoroughly peer reviewed. This includes publication in peer-reviewed journals, peer review and adoption by the EPA (EPA 2001), and by an independent panel. This included the FRG-initiated peer review of model performance that was managed by the American Geological Institute (AGI). To the greatest extent practical, peer review panel recommendations were integrated into wLFRM development efforts.

Note that the wLFRM uses estimates of hydrodynamics (flow velocities), sediment transport (shear stresses, erosion, and deposition), sediment mixing, and PCB transport that are consistent with field observations and other studies of these conditions for all four reaches of the Lower Fox River. Development and calibration of the wLFRM was performed on a reach-by-reach basis. Comparisons of observed conditions and model results were developed for each of the four reaches used in the RI/FS: Little Lake Butte des Morts (Lake Winnebago to Appleton), Appleton to Little Rapids, Little Rapids to De Pere, De Pere to Green Bay. In this regard, the wLFRM described PCB transport for each of the four reaches of the River.

Also note that the performance of the wLFRM is consistent with the evaluation metrics developed in collaboration with the FRG. Model performance was evaluated according to the metrics identified in Technical Memorandum 1 (LTI and WDNR, 1998), a collaboratively developed Workgroup product. For the water column, the overall relative difference between observed solids and PCB concentrations and model results was within ±30 percent. While relative differences for the sediment column were much larger, it is important to understand how the observations and model results used to assess model performance were interpreted. Successful application of a given evaluation metric depends on how closely the interpretation of field data represent the true condition of the River as well as whether the spatial and temporal scale of observations and model results are comparable. In this regard, the wLFRM was able to capture the trend and magnitude of inferred PCB concentration trends in surface sediments and net burial rates. Given these considerations, the wLFRM calibration was judged to adequately meet the criteria identified in Technical Memorandum 1.

Finally, the wLFRM accurately represents the most critical features of Lower Fox River Site conditions. As demonstrated by the results of field sampling efforts, the only significant present-day source of PCBs to Lower Fox River is the River sediments. PCB concentrations in River water are essentially zero at the upstream boundary with Lake Winnebago and increase to an average of more than 50 ng/L at the River mouth. The wLFRM reproduces the sediment origin of PCBs as well as the trend and magnitude of PCB concentrations in the water column and sediment.

In consideration of the qualities described above, use of the wLFRM was judged to be appropriate as an indicator of the relative trend and magnitude of PCBs concentrations and export in the Lower Fox River. In this context, the year-by-year, reach-by-reach resolution of this model was considered sufficient to meet overall project goals. In consideration of model performance strengths and limitations, the wLFRM calibration was considered to provide a reasonable description of PCB concentrations and export in the Lower Fox River on a year-by-year, reach-by-reach basis. Given the level of documentation, peer review, consistency with observed conditions in the River, and performance relative to the collaboratively developed model performance metrics, WDNR believes that wLFRM is suitable for its intended use within the RI/FS, the Proposed Plan, and ROD.

5.2 RESPONSE TO COMMENTS

As part of the public response to the RI/FS, WDNR and USEPA received comments from the Fox River Group (FRG) of Companies and their consultants that claim the computer modeling supporting the RI/FS and Proposed Plan analysis is flawed. Specifically citing the wLFRM, these commenters argued that the wLFRM:

1. Is not adequately documented or developed;
2. Does not appropriately track sediment PCB concentrations over the calibration period;
3. Overstates the shear stress and amount of resuspension;

4. Does not account for releases of PCBs during dredging; and

5. Does not account for residual PCB concentrations post-dredging.

In addition to these broadly generalized categories of comments, WDNR and USEPA also received specific comments from the FRG, individual FRG companies, and their consultants that were critical of a range of other wLFRM performance issues. Responses to the broad comment categories and specific comments are presented below. In developing responses to comments, the main concern of WDNR and USEPA was whether: (1) information provided would significantly alter the possible range of model parameter values such that the calibrated values used in the wLFRM would be outside the range of acceptable values; (2) proposed alterations to the model formulation are technically sound and would result in a demonstrably superior model and not just simply a different model; and (3) differences in model results would materially affect RI/FS conclusions or the management decisions presented in the Proposed Plan, or ROD.

5.2.1 Response to Broadly Generalized Comments Regarding the wLFRM

With respect to the adequacy of model development, note that the wLFRM represents the fourth generation of model development specific to PCB transport in the Lower Fox River. In addition to extending the efforts of three prior generations of development, the wLFRM was itself the result of several years of development efforts that included the direct, collaborative involvement of the FRG and consultants through the Model Evaluation Workgroup. Workgroup findings, presented in numerous Technical Memoranda, provided the basis for nearly all aspects of model development. With respect to the adequacy of model documentation, the RI/FS (RETEC, 2002a, 2002b) and associated Model Documentation Report (WDNR and RETEC, 2002) include all Workgroup Technical Memoranda and reports specific to wLFRM development and calibration, and documentation of the IPX 2.7.4 framework. These reports provide several thousand pages of documentation for the wLFRM. In addition, three peer-reviewed journal publications and numerous other reports provide additional documentation of wLFRM history and development. Given this high level of development and documentation, WDNR believes that claims suggesting that the wLFRM is not adequately developed or documented do not have a sound basis.

With respect to the ability of the wLFRM to appropriately track sediment PCB concentrations during the calibration period, note that simulated reach averaged surface sediment PCB levels in the wLFRM fall within, and never exceed, the 95 percent confidence intervals of observed PCB levels. Considering the area between the De Pere dam and the River mouth (Reach 4), the upper 95 percent confidence limit of the observations is more than 60 percent larger than the average.[13] Model results for Reach 4 never exceed the 95 percent confidence limit of observed PCB levels for this reach. The small (~1 mg/kg) difference in model results over time is more a reflection of the spatial

[13] The average PCB concentration in the 0-10 cm sediment layer of Reach 4 is 4.0 mg/kg. The upper 95 percent confidence limit of the average value is 6.6 mg/kg. Observed concentrations in Reach 4 (232 values) are lognormally distributed. The average and 95 percent confidence limits were computed as from the log-transformed data, detransformed to normal space, and corrected for detransformation bias. The upper 95 percent confidence limit is 64 percent larger than the mean value.

heterogeneity of the observations rather than any failure of the model to appropriately track surface sediment PCB levels. Perhaps more significantly, it should be also be noted that this FRG comment regarding the ability of the a model to track PCB levels is based on the flawed and demonstrably incorrect premise that PCB concentrations in sediments can never increase over time. At any location where PCB levels immediately below the surface-most sediments exceed the PCB levels found in surface sediment, the possibility for PCB increases exists. Any time bed elevation decreases occur at that location, the average PCB concentration in the top 10 cm of sediments will increase. As conclusively demonstrated by Technical Memorandum 2g (WDNR, 1999c) and follow-up efforts, such decreases in sediment bed elevations are common in the Lower Fox River. Given that wLFRM performance falls within the 95 percent confidence limit of the observations and that sediment bed elevations decreases do occur and may cause PCB levels in surface sediments to increase, WDNR believes that claims suggesting the wLFRM does not appropriately track sediment PCB levels are unsupported.

Further, it must be recognized that the main pathway for risk in the Lower Fox River is PCB exposure via the water column. As part of calibration, PCB levels in the water column and sediment bed were both considered. Once model results for both the water column and sediment bed met the model performance criteria established in Technical Memorandum 1 (LTI and WDNR, 1998), the model calibration was considered acceptable. Despite the greater uncertainty of model results for the sediment column, model performance for sediment PCB levels is nonetheless acceptable. More importantly, model performance for the central risk pathway, water column PCB exposures, is quite good. Again, in light of all these factors, WDNR and EPA believe that claims suggesting the wLFRM does not appropriately track sediment PCB levels are unsupported.

With respect to the ability of the wLFRM to represent shear stresses and erosion amounts, it should be noted that these aspects of wLFRM development are based on results of hydrodynamic and sediment transport model developed for the Site as described in Technical Memoranda 5b (Baird, 2000a), 5c (HydroQual, 2000), and 5d (Baird, 2000b). The results of these hydrodynamic and sediment transport models were used to develop the wLFRM. As documented by WDNR (2001a) and as shown in Table 4-1 of this White Paper, the close agreement (17 percent overall difference) between simulated and observed solids levels at each monitoring in the River demonstrates that the wLFRM adequately represents sediment transport in the River. Given this level of agreement, WDNR believes that shear stresses and erosion amounts are appropriately represented in the wLFRM. Further discussion of these issues with respect to specific comments regarding the representation of shears stresses and erosion is presented in Section 5.2.2 of this White Paper.

With respect to the representation of PCB releases during dredging, note the wLFRM represents remediation by a series of alternative-specific targets for post-remediation sediment bed elevations and PCB concentrations initially at depth in the sediment bed. The wLFRM does not explicitly simulate dredging. As discussed in *White Paper No. 9 – Remedial Decision-Making for the Lower Fox River/Green Bay Remedial Investigation, Feasibility Study, Proposed Remedial Action Plan, and Record of Decision* (WDNR, 2002a), PCB releases during dredging are expected to be very small relative to existing levels of PCB transport in the Lower Fox River. In particular, it should be noted that during the Deposit N and SMU 56/57 demonstration projects, the mass of PCBs released by dredging was roughly two orders of magnitude smaller (less than 1 percent) than the present level of ongoing PCB transport through the Lower Fox River. Assuming full-scale dredging operations were initiated, direct releases of PCBs during dredging (a few kilograms per year) would always be far smaller than natural transport rates (several hundred kilograms per year). Further, as documented by the Sediment Technologies supporting study of the RI/FS (RETEC, 2002a, 2002b), direct PCB releases during dredging can be minimized by the use of careful controls during dredging. Given these observations, the effect of PCB releases during dredging and the impact of PCBs potentially present in post-dredge patina layers were considered negligible.

With respect to the representation of residual surface sediment PCB concentrations immediately following dredging, note the wLFRM represents remediation by a series of alternative-specific targets for post-remediation sediment bed elevations and PCB concentrations. Patinas (thin residual layers) of more-highly PCB-contaminated sediments were not explicitly included in the wLFRM based on consideration of the ability of dredging technologies to achieve low residual PCB concentrations and the rapid rate at which conditions at the sediment-water interface are expected to change following dredging. In particular, as monitored following first phase of the SMU 56/57 demonstration project in 1999, PCB concentrations in portions of the dredged area where post-dredging bed elevation meet the target elevation were approximately equal to PCB concentrations initially present at that sediment depth (WDNR, 2000c). Further, post-dredging monitoring of the SMU 56/57 site showed that rapid changes in the sediment-water interface occurred over time and that conditions a few months following dredging did not resemble conditions immediately following dredging (WDNR, 2002b). Given these observations, the effect of PCB releases during dredging and the impact of PCBs potentially present in post-dredge patina layers were considered negligible.

Finally, it should also be noted that FRG comments regarding PCB releases and residual PCB levels are based on the flawed premise that remediation actions involving dredging must always occur in a manner that causes large PCB releases and that dredging efforts will always fail to achieve the targets set for remediation. As noted above, substantial site-specific information exists to demonstrate that PCB releases during dredging are small and that low residual PCB levels can be achieved. Given this information, WDNR believes that FRG claims regarding PCB releases and residuals are unjustified.

5.2.2 Responses to Specific Comments

Responses to specific comments from the FRG, individual FRG companies, and their consultants are presented below. In developing responses to comments, the main concern of WDNR and USEPA was whether: (1) information provided would significantly alter the possible range of model parameter values such that the calibrated values used in the wLFRM would be outside the range of acceptable values; (2) proposed alterations to the model formulation are technically sound and would result in a demonstrably superior model and not just simply a different model; and (3) differences in model results would materially affect RI/FS conclusions or the management decisions presented in the

PROPOSED PLAN or ROD. Where possible, similar comments were grouped and paraphrased to permit presentation of more concise responses.

Comment:

The wLFRM prediction of PCB sediment concentrations under the "no action" alternatives does not reflect the strong and continuing downward trend shown by actual sediment data. As a result, the model underestimates the degree to which natural attenuation is occurring.

Response:

The claim that strong and continuing downward trends in Lower Fox River sediment PCB levels exist is not supported by observations. Surface sediment PCB trends were examined in two different supporting studies as part of the RI/FS. As documented by Appendix B of WDNR (2001a), no clear trends exist. At different locations, surface sediment PCB levels may appear to increase, decrease, or stay the same. Similar findings were also reported by TMWL (2002). As summarized in Section 2.2 of this White Paper, four conclusions that may be drawn from these data: (1) a spatial trend of generally decreasing sediment PCB concentration with distance from Lake Winnebago exists; (2) apparent PCB concentration changes over time may reflect the spatial heterogeneity of PCBs in the sediments; (3) at any individual location, sediment PCB concentrations may increase, decrease, or stay the same over time; and (4) the overall rate at which surface sediment PCB concentrations change over time is slow. It should also be noted that in attempting to justify their claim, the commenters relied on inappropriate combinations of data. Over time, data were collected at different locations, from different strata, and using different sample collection and analytical protocols. Biases introduced as a result of these methodological differences are more than large enough to account for any trends the commenters inferred. A brief discussion of these biases is provided by WDNR (2001a). In light of the failure of the commenters analyses to even identify, let alone account for, methodological differences, WDNR and EPA believe that the trend assessments that the trends assessments performed as part of the RI/FS are far more reliable.

Comment:

Both the ECOM-SED model and the RMA model predict substantially lower shear stress and depths of scour near the banks of the River.

Response:

This comment overstates the differences between hydrodynamic model results and conditions in the wLFRM. The wLFRM uses flow-velocity relationships developed from the results of hydrodynamics models to estimate shear stresses and erosions amounts (from which depth of scour is estimated). These flow-velocity relationships relate average hydrodynamic velocities over the surface area of each sediment deposit, interdeposit area, and sediment management unit (SMU) to the average flow. The average value used in the wLFRM will represent the average hydrodynamic value that occurs over any sediment area. It is therefore important to recognize that the hydrodynamic models and the wLFRM have different spatial scales. Within any wLFRM segment, hydrodynamic model results can be somewhat larger or smaller than the average value. However, when hydrodynamic model grid cells within a given wLFRM segment are appropriately averaged, there is a direct correspondence between the hydrodynamic model results and the wLFRM.

ECOM grid cells are much smaller (~60 m by 90 m) than those needed to develop the wLFRM (~400 m by 1,000 m). To make long-term simulations computationally feasible, the wLFRM was developed with a coarser spatial scale than ECOM. ECOM results were averaged over wLFRM water column segments to produce relationship between velocity and average flow. Averaging is also necessary because: (1) flow is the only parameter for which a long-term record exists from which velocity can be estimated; and (2) the long-term flow observations (1954-1995) include conditions which did not occur during the ECOM (TM5b, TM5c) 1989-1995 calibration period. As a result of spatial averaging some fine-scale detail is lost. However, average velocities are preserved. By definition of an average quantity, for each case where the velocities at individual ECOM grid cells are less than the average velocity of a wLFRM segment, there are an equal number of locations were velocities at ECOM grid cells exceed the wLFRM average velocity. Perhaps more importantly, it is worth noting that the purpose of the wLFRM was to provide insight into the relative trends and magnitudes of PCB concentrations over time on a reach-by-reach basis. For this spatial and temporal scale, use of average velocity values is very reasonable. Also, proposed remedial strategies are provided on a reach-by-reach basis. Sediment management on a 60 m by 90 m scale is impracticable. Even if remediation on such a fine scale were practicable, preservation of ECOM (or RMA) results at the full spatial and temporal resolution of the two-dimensional hydrodynamic model is of questionable value. The flow structure of a natural system is three-dimensional as secondary and helicoidal flows and other conditions occur. Vertically averaged, two-dimensional hydrodynamics models do not resolve such flow features (see Lane et al. 1999). Under such conditions, retaining the full precision of a two-dimensional hydrodynamic approximation provides no additional accuracy; representing an approximation with more significant figures does not improve the underlying accuracy of the approximation.

Comment:

The wLFRM predicts steady erosion in roughly 20 sediment bed segments in the center navigation channel of the River below the De Pere dam. For decades, it has been necessary for the USACE to dredge this navigation channel to keep the channel open for commercial traffic. Thus, many of the specific areas that wLFRM assumes to be erosional are the same areas the USACE must dredge regularly to remove new deposits.

Response:

It is important to note that this comment misrepresents the extent of dredging and locations where dredging has occurs in the Lower Fox River over the past 30 years. The only areas are the navigation channel where dredging has routinely occurred are the Fort James (Georgia Pacific) and East River turning basins. As documented in TM2g (WDNR, 1999c), much of the navigation channel has not been dredged in 30 years. Of those few locations where dredging has occurred, many of those areas have been dredged once. The reason dredging has not occurred in much of the navigation channel is because sediment bed elevations have either been relatively constant or have decreased over time. While observed bed elevations are more dynamic than wLFRM results (or the results of any sediment transport model developed for the Site), the model typically represents the direction of bed elevations changes over time as shown in Table 4-5 of WDNR (2001a) and Section 4.2.2.1 of this White Paper.

Comment:

The wLFRM improperly uses a mixing depth of 30 cm, and should instead use a 10-cm mixing depth. The draft Model Documentation Report dated October 2001 does not provide any justification for the assumption of a 30-cm mixing depth. The literature "standard" for mixing is 10 cm and should be used.

Response:

As described in Section 2.5 of this White Paper, mixing depths used in the wLFRM are well supported by field data. Observed sediment mixing depths vary widely. While typical mixing depths range from 10 to 30 cm, sediment disturbances of up to 200 cm have been observed. It should be noted that this comment falsely asserts that a "standard" sediment mixing depth exists. This assertion is based on the false premise that mixing is almost exclusively driven by biological processes and other processes do not disturb the sediment bed. However, contrary to this premise, other processes such as bed elevation changes due to flow events, density currents, and sediment slumping can also disturb and mix sediments. As described in TM2g (WDNR, 1999c) and follow-up efforts (WDNR, 2001a), sediment bed elevations in the Lower Fox River are very dynamic. Over monthly to annual times scales, sediment bed elevations have been observed to regularly fluctuate between 10 to 30 cm. Larger fluctuations of approximately 200 cm have also been recorded over annual time scales. Over broad areas, the net change in bed elevation is very small. This means that at each location where a large decrease in bed elevation occurs, there is typically a nearby location with a correspondingly large increase in elevation. Consequently, within the same general area there is a pattern of mixing where particles and contaminants located deeper within the sediment column can return to the sediment surface and materials initially at the surface are buried until the next disturbance occurs. In addition to bed elevation data, the periodic disturbance of sediments to considerable depth in the sediment column is supported by the Cesium-137 (Cs-137) profile results reported by Steuer et al. (1995) that show sediment disturbances to depths of approximately 40 cm. It should also be noted that data provided by the comment documents mixing depths of up to 20 cm from locations where intact Cs-137 profiles could be obtained. Given the large number of observations that indicate sediment mixing depths are variable and that sediment disturbances of up 200 cm can occur, WDNR and EPA believe the claim that sediment mixing depths are limited to 10 cm is not defensible.

Comment:

The wLFRM's segmentation of the sediment bed is flawed because initial segment thicknesses in the model vary from 5 cm at the surface to 50 cm at depth. As a result, the mixed depth of sediment increases significantly over time in some areas, exacerbating the effects of the 30-cm mixing depth error. The use of uneven strata makes the wLFRM incapable of accurately reflecting surface sediment concentrations when erosion occurs.

Response:

As described in Section 2.5 of this White Paper, the depth to which sediment mixing or other disturbances may occur is not constant and varies widely by location and over time. The most straightforward method to represent variability in the depths of sediment disturbances was the use of sediment segments that increase in thickness with depth below the sediment-water interface. By use of this segmentation approach, the sediment mixing depth in and sediment stack can vary in response to the extent of erosion or deposition that occurred. Areas subject to larger disturbances will take on a larger mixing depth and areas subject to less extensive disturbances will take on a smaller mixing depth. Given the observed extent and variability of sediment mixing depths as summarized by WDNR (2001a), Section 2.5 of this White Paper, and LTI (2002), WDNR and EPA believe that mixing depths are appropriately represented in the wLFRM.

Comment:

Application of the wLFRM results in an artificial buildup of PCB mass in the surface sediment layers.

Response:

As previously noted, WDNR and EPA believe the commenters have misrepresented the nature of wLFRM results. With respect to the ability of the model to track sediment PCB levels over the calibration period, it is important to note that simulated reach-averaged surface sediment PCB concentrations are within the 95 percent confidence intervals of observed PCB levels. Considering the area between the De Pere dam and the River mouth (Reach 4), the upper 95 percent confidence limit of the observations is more than 60 percent larger than the average as previously noted. Model results for Reach 4 never exceed the 95 percent confidence limit of observed PCB levels for this reach. The small (~1 mg/kg) difference in model results over time, described as an "artificial buildup" by the commenters, is more a reflection of the spatial heterogeneity of the observations rather than any failure of the model to appropriately track surface sediment PCB levels. Because model results do not fall outside the confidence limits of the initial condition, the proper interpretation of wLFRM results is that the model predicts little change in surface sediment PCB levels over time. Such a result and interpretation is consistent with the surface sediment PCB trends analyses presented in the RI/FS.

Perhaps more significantly, note that this comment is based on the flawed premise that PCB levels in sediments can never increase over time. In contrast to this premise, note that at any location where PCB levels immediately below the surface-most sediments exceed the PCB levels found in surface sediment, the possibility for PCB increases exists. Any time bed elevation decreases occur at that location, the average PCB concentration in the top 10 cm of sediments will increase. As conclusively demonstrated by Technical Memorandum 2g (WDNR, 1999c) and follow-up efforts, such decreases in sediment bed elevations are common in the Lower Fox River. Given that wLFRM performance falls within the 95 percent confidence limit of the observations and that sediment bed elevations decreases do occur and may cause PCB levels in surface sediments to increase, WDNR and USEPA believe that claims suggesting the wLFRM does not appropriately track sediment PCB levels are unsupported.

Further, it must again be recognized that the main pathway for risk in the Lower Fox River is PCB exposure via the water column. As part of model calibration, both the water column and sediment bed were considered. Once model results for water and sediment met the model performance criteria established in Technical Memorandum 1 (LTI and WDNR, 1998), the model calibration was considered acceptable. Despite the greater uncertainty of model results for the sediment column, model performance for sediment PCB levels is nonetheless acceptable. More importantly, model performance for the central risk pathway, water column PCB exposures, is quite good. Again, in light of all these factors, WDNR and EPA believe that claims suggesting the wLFRM does not appropriately track sediment PCB levels are unsupported.

Comment:
The wLFRM does not adequately represent the relationship between sediment volumes and exchange areas in subsurface sediment layers. They content that this leads to greater rates of erosion in some areas.

Response:
This comment is incorrect and entirely mischaracterizes the operation of the IPX 2.7.4 modeling framework and the performance of the wLFRM. Surface areas for all sediment layers in the wLFRM vary as determined from field data. As erosion and deposition occur during a simulation, the IPX 2.7.4 framework always uses the appropriate surface area of the sediment segment to compute the mass flux of material to or from each sediment segment. The IPX 2.7.4 framework appropriately manages sediment surface areas (and all other properties) regardless of whether erosion or deposition occurs in a segment. Management of sediment stack properties within IPX 2.7.4 is performed in Subroutines PUSH and POP. Sections 1.5.3.2 and 1.5.4.2 of the IPX 2.7.4 user's manual (USEPA, 2001) describe the operation of these subroutines. Further, examination of model source code for these two subroutines shows that sediment properties are appropriately managed. Therefore, the claim that the relationships between sediment segment volumes and surface areas are not properly represented in the wLFRM is false.

Comment:
The wLFRM does not include any modeling process to account for pore water diffusion.

Response:
Porewater diffusion is one of the possible mass transfer pathways for PCBs in the sediments. This process is included in the conceptual model framework as described by WDNR (2001) [the wLFRM report in the MDR]. Porewater transfers can move dissolved PCBs between sediment layers and to the water column. In the wLFRM, PCB porewater transfer functions were specified between layers in the sediment column. However, due to an oversight when the model input data files were constructed, the final

linkage between the surface sediments and the water column was not specified. Note that porewater diffusion can only transport dissolved and bound phase PCBs. Also note that PCBs are strongly associated with particles because they are hydrophobic and that less than 1 percent of the PCBs in the sediments are expected to be associated with dissolved and bound phases. As a result, the impact of this oversight is expected to be very small.

Comment:

The wLFRM should have accounted for dredging processes, including PCB remobilization during dredging, and residual PCB concentrations post-dredging. The FS modeling forecasts of dredge scenarios assumed PCB releases during dredging to be zero, which then results in overestimating removal relative to Monitored Natural recover (MNR). In addition, the wLFRM should have explicitly accounted for post-dredging PCB sediment concentrations.

Response:

With respect to the representation of PCB releases during dredging, note the wLFRM represents remediation by a series of alternative-specific post-remediation sediment bed elevations and PCB concentrations initially at depth in the sediment bed. The wLFRM does not explicitly simulate dredging. As discussed in *White Paper No. 9 – Remedial Decision-Making for the Lower Fox River/Green Bay Remedial Investigation, Feasibility Study, Proposed Remedial Action Plan, and Record of Decision* (WDNR, 2002a), PCB releases during dredging are expected to be very small relative to existing levels of PCB transport in the Lower Fox River. In particular, it should be noted that during the Deposit N and SMU 56/57 demonstration projects, the mass of PCBs released by dredging was roughly two orders of magnitude smaller (less than 1 percent) than the present level of ongoing PCB transport through the Lower Fox River. Assuming full-scale dredging operations were initiated, direct releases of PCBs during dredging (a few kilograms per year) would always be far smaller than natural transport rates (several hundred kilograms per year). Further, as documented by the Sediment Technologies supporting study of the RI/FS (RETEC, 2002a, 2002b), direct PCB releases during dredging can be minimized by the use of careful controls during dredging. Given these observations, the effect of PCB releases during dredging were considered negligible.

With respect to the representation of residual surface sediment PCB concentrations immediately following dredging, again note the wLFRM represents remediation as a series of alternative-specific post-remediation sediment bed elevations and PCB concentrations. Patinas (thin residual layers) of more-highly PCB-contaminated sediments were not explicitly included in the wLFRM based on consideration of the ability of dredging technologies to achieve low residual PCB concentrations and the rapid rate at which conditions at the sediment-water interface are expected to change following dredging. In particular, as monitored following first phase of the SMU 56/57 demonstration project in 1999, PCB concentrations in portions of the dredged area where post-dredging bed elevation meet the target elevation were approximately equal to PCB concentrations initially present at that sediment depth (WDNR, 2000c). Further, post-dredging monitoring of the SMU 56/57 site showed that rapid changes in the sediment-water interface occurred over time and that conditions a few months following dredging did not resemble conditions immediately following dredging (WDNR, 2002b). Given these observations, the effect of PCB releases during dredging and the impact of PCBs potentially present in post-dredge patina layers were considered negligible.

In consideration of the monitoring results obtained during Lower Fox River demonstration projects, and the rapid change of Site conditions following remediation, WDNR and EPA believe that the representation if remediation is appropriate to permit the evaluation of relative differences between management alternatives in the RI/FS, Proposed Plan, and Record of Decision.

6 CONCLUSIONS

The following conclusions regarding wLFRM development and performance are offered:

1. Development of the wLFRM is consistent with the information developed by the Model Evaluation Workgroup (Workgroup). The wLFRM was developed collaboratively through multiple governmental, university, and industry workgroups. The development history of the model framework and its application to the Lower Fox River has been extensively documented. The wLFRM in particular was developed from the results of the Workgroup formed in collaboration with the Fox River Group (FRG) of Companies on the basis of a January 1997 Agreement. The Workgroup prepared a series of reports that define values for critical model features such as flows, loads, initial conditions, boundary conditions, and sediment transport. The Workgroup reports listed in Table 3-1 represent the most detailed description possible of pertinent River conditions using existing data and provided the majority of the information necessary for model development.

2. Development of the wLFRM is consistent with peer-reviewed journal publications and is also consistent with the recommendations of a peer review panel. The wLFRM and IPX 2.7.4 framework have been thoroughly peer reviewed. This includes publication in peer-reviewed journals, peer review and adoption by the EPA (EPA 2001), and by an independent panel. This included the FRG-initiated peer review of model performance that was managed by the American Geological Institute (AGI). To the greatest extent practical, peer review panel recommendations were integrated into wLFRM development efforts. In addition to these publications, the wLFRM is consistent with AGI peer review panel recommendations that the model: (1) use a single spatial domain to describe PCB transport in all 39 miles of the Lower Fox River from Lake Winnebago to the River mouth at Green Bay; (2) avoid "deep mixing" of sediment by using the IPX 2.7.4 framework (USEPA, 2001); and (3) simulate solids as (at least) three state variables.

3. The wLFRM uses estimates of hydrodynamics (flow velocities), sediment transport (shear stresses, erosion, and deposition), sediment mixing, and PCB transport that are consistent with field observations and other studies of these conditions for all four reaches of the Lower Fox River. Model development and calibration of the wLFRM was performed on a reach-by-reach basis. Comparisons of observed conditions and model results were developed for each of the four reaches used in the RI/FS: Little Lake Butte des Morts (Lake Winnebago to Appleton), Appleton to Little Rapids, Little Rapids to De Pere, De Pere to Green Bay.

4. The performance of the wLFRM is consistent with the evaluation metrics developed in collaboration with the FRG. Model performance was evaluated according to the metrics identified in Technical Memorandum 1 (LTI and WDNR,

1998), a collaboratively developed Workgroup product. For the water column, the overall relative difference between observed solids and PCB concentrations and model results was within ±30 percent. Relative differences for the sediment column were much larger. However, when making comparisons, it is important to understand how the observations and model results used to assess model performance were interpreted. Successful application of a given evaluation metric depends on how closely the interpretation of field data represent the true condition of the River as well as whether the spatial and temporal scale of observations and model results are comparable. In this regard, the wLFRM was able to capture the trend and magnitude of inferred PCB concentration trends in surface sediments and net burial rates. Given these considerations, the wLFRM calibration was judged to adequately meet the criteria identified in Technical Memorandum 1.

5. The wLFRM accurately represents the most critical features of Lower Fox River Site conditions. To accurately represent the Site, a model must agree with observations that demonstrate the origin of PCBs from River sediments and the general trend and magnitude of PCB concentrations in River water. As demonstrated by the results of field sampling efforts, the only significant present-day source of PCBs to Lower Fox River is the River sediments. PCB concentrations in River water are essentially zero at the upstream boundary with Lake Winnebago and increase to an average of more than 50 ng/L at the River mouth. The wLFRM reproduces the sediment origin of PCBs as well as the trend and magnitude of PCB concentrations in the water column and sediment.

6. The use of the wLFRM was judged to be appropriate as an indicator of the relative trend and magnitude of PCBs concentrations and export. In this context, the year-by-year, reach-by-reach resolution of this model was considered sufficient to meet overall project goals. In consideration of model performance strengths and limitations, the wLFRM calibration was considered to provide a reasonable description of PCB concentrations and export in the Lower Fox River on a year-by-year, reach-by-reach basis. Given the level of documentation, peer review, consistency with observed conditions in the River, and performance relative to the collaboratively developed model performance metrics, WDNR believes that wLFRM is suitable for its intended use within the RI/FS and as a tool to support the selection of a remedy in the ROD.

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